COMPUTER PROGRAMMING FOR COOLING TOWER PERFORMANCE

by

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AUGUST 1983

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FOR
COOLING TOWER PERFORMANCE

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

by

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to the

Department of Mechanical Engineering
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

AUGUST, 1983

CERTIFICATE

This is to certify that the thesis entitled, " Computer Programming for Cooling Tower Performance" by Mr. K.A. Nagabushana is a record work carried out under my supervision and the same has not been submitted elsewhere for a degree.

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ACKNOWLEDGEMENTS

I express my appreciation and gratitude to:

My supervisor, Dr. MANOHAR PRASAD, whose continuous encouragement, guidance and enthusiasm were vital to the success of this effort,

Computer Centre, IIT, Kanpur for computational facilities,

Dr. B. Sahay and V. Sundararajan for their timely help in the last moment,

Mr. R.K. Nakrani, V. Somasundaram, Srikanth Jain, R. Rajaram Prasad and other friends in preparing this manuscripts,

Mr. P.N. Misra and P.N. Sharma for their constant encouragement and useful information,

Mr. D.P. Saini for nice typing of the manuscript.

K.A. NAGABUSHANA

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NOMENCLATURE

A	-	Tower reference plan area
BLD	-	% Blowdown of water/hr
CFIL	-	Cost of wood/m^3
COP	-	Cost of power/KW-hr
CWAT	-	Cost of water/m^3
CWOOD	-	Total cost of wood
C1,C2,C3,C4	-	Constants depending upon the type of fill arrangement
D	-	Diameter of water droplet in mm
d	-	Diameter in m
GE	-	Equivalent mass of air
g	-	Acceleration due to gravity in m/sec^2
HEAD	-	Total pumping head
HR	-	Number of hours/year
h	-	Enthalpy in kcal/kg of dry air
k	-	Thermal conductivity in kcal/m-hr-°C
Le	-	Lewis number $h_c/(h_D\ c_{pa})$
LKG	-	% leakage of water/hr
M	-	Number of elements in i direction
m	-	Mass flow in tower - kg/hr
N	-	Number of elements in j direction
n	-	Number of decks
OF		Tower operating factor

P Pressure in N/m^2

VOLSEC Volume of air blown/sec

POWFAN – Power for fan in KW-hr

PPOW – Power for pump in KW-hr

Pr – Prandtl number

PUMCOS – Cost of pumping

Re – Reynolds number

T – Temperature in °C

TOTWAT – Total water required/year

V – Total volume of tower in m^3

VOLF – Volume of fill in m^3

VSEC – Face velocity in m/sec

W – Humidity in kg of water/kg of dry air

WATCOS – Cost of water/m^3

x – Mol-fraction of air in moles dry air/ moles moist air

X – Number of Years

A_v – Surface area of water droplet in m^2/m^3

C_o – Total cost over projected life

C_p – Specific heat in kJ/°C-kg of dry air

C_t – Total cost of tower for the projected life

t_r – Pipe frictional co-efficient

q_c – Universal gravitational constant

h_c – Heat transfer coefficient in kcal/hr-m^2-°C

h_D – Mass transfer co-efficient in kg of dry air/hr m^2

K_e		Combined heat and mass transfer coefficient
r_{Int}	-	Rate of discount
V_r	-	Relative velocity of air
Z_f	-	Distance between each deck in m.
ΔP	-	Pressure drop in mm of water
ΔV	-	Elemental volume of tower in m^3
ρ	-	Density in kg/m^3
ν	-	Kinematic viscosity in stokes
μ	-	Absolute viscosity in kg/m-sec

SUFFIX

a	-	air
av	-	average value
db	-	dry bulb
e	-	equivalent
ev	-	evaporation
f	-	saturated liquid state
fg	-	evaporated state
g	-	saturated vapour state
i	-	number of row
j	-	number of column
pip	-	pipe
re	-	rate of evaporation
s	-	saturated condition
wb		wet bulb

ABSTRACT

The governing equations for a cross and counter-flow cooling towers are derived using heat and mass transfer considerations. The finite element method was used to solve these equations for various ranges of parameters. The optimum number of fills were determined for a desired exit water temperature using iterative scheme.

In case of a given exit condition of water the NTU and tower characteristics were also determined using variable as well as fixed mass of water. When the evaporation of water was considered, it was found that the tower capacity gets increased by about 6 to 7%.

The effects of Lewis number shows significant effect on the exit conditions based on recommended Lewis numbers. Hence the present method considering the variable/average Lewis number should be used for the evaluation of the tower characteristics.

Finally, cost analysis has been carried out for constraints like water load, fills, etc., considering over a period of the tower life. It has been found that the make up water dominates over costs of power, machinery and packing material.

CHAPTER - I

INTRODUCTION

1.1 Need for Cooling Towers [4, 13, 14, 19, 30]

The disposal of waste heat is a most common feature in power plants, refrigeration systems and industries. In many processes it is even necessary to dispose of heat from certain part of the plant

1. in order to get rid of the local temperature gradient

2. the vast quantity of heat generated cannot be put to good use for various reasons.

At the same time with the industrial progress the need for cooling equipment with sophisticated designs have grown up for the process of heat removal. Water and air are readily and naturally available in abundance as cheapest agencies. Owing to gaseous nature,greater quantities of air is required to perform the same function as water. Thus water is generally chosen as a cooling media.

In thermal power plants each MW of power generation demands 2 MW of heat rejection. Similarly, in vapour

compression refrigeration systems each ton of cooling requires about 1.3 ton of heat rejection. If air is used to reject 2 MW of heat with about 10°C of temperature rise, one needs 2000 kg/s of air as compared to only 500 kg/s of water. In olden days, due to this large requirement of water and lack of knowledge of cooling towers, the industries were situated at the water resources, like - lakes, large ponds, canals, river etc. The abundant water resources made it possible to use cold water on once through basis. However, the number of rivers and lake sites are limited, and the average temperature of such water frequently rises owing to growing number of plants. Also in many countries in the light of ecological renaissance it is environmentally unacceptable to discharge hot water directly to source after its use for cooling. The hot process water must be either cooled before discharge or cooled and recycled. Purchasing and then discharging large quantities of water into sewage systems is cost prohibitive. Even if favourable economically, such practice is socially restricted and environmentally prohibitive. Moreover the site selection for an industry may prove to be profitable to locate it where water is scarce. It implies therefore to develop a system which can cool the warm water with least use of make up water. This has led to the development of evaporative cooling device-Cooling Tower.

1.2 Historical Background and Development in Cooling Towers [6,14, 16, 18, 19]

In spite of present widespread and continually growing use of cooling towers for heat dissipation in various industries comparably less information was available in the past. The development, as a whole or in part, took place within last century. Water has always been the most convenient medium for removing the heat, and recooling became necessary as the required quantity of cooling water increased.

Cooling towers function on the principle of evaporative cooling. Although the art of evaporative cooling is quite ancient, it has been studied scientifically very recently. The first use of evaporative cooling dates back to 2500 B.C., where the porous jars were used to get cool water. In persian countries it was customarily to cover their tents with wet felt in order to find shelter from oppressive heat. And the permanent houses were built half underground and running water was flown into a small indoor pool. The same principle of evaporative cooling was made use of in making ice in olden days.

After continual development it was discovered that by spraying downwards in a box, instead of upwards,

instead of relying on prevailing winds for air movement in spray ponds and atmospheric spray towers, aerodynamically designed fans were incorporated into the system. The betterment in system was brought about by fill or packing material to increase the retention time of water and provide greater air/water interfacial contact for more efficient cooling.

Cooling tower technology appears to have made an entire circle, as emphasis is again directed towards atmospheric cooling. However, there are significant differences in these modern designs compared to early prototype. The hyperbolic cooling towers are being constructed, now-a-days, without the use of fans or air movers.

1.3 Literature Survey [5, 6, 14]

The first technical consideration of the problem was given by Robinson C.S., in 1922. It was further developed by Walker, Lewis and McAdams in the following years. They developed the basic governing equations for Heat and Mass transfer as two different processes in the tower design, and developed an interesting relationship between Heat and Mass transfer co-efficients, but did not use. Later Lewis W.K., found the same relationship and was named after him as " LEWIS'S LAW",

$$Le = f \text{ (Conductivity/Diffusivity)}$$
$$= h_c/(h_d * c_{pa})$$

During the same year it was noted by Nusselt W., and was verified by Schmidt E. In the case of water evaporating into air, conductivity is approximately equal to diffusivity, so that their ratio is unity. Montgomery R.B., finds it equal to 0.84 and Hansen H., puts it at 0.94.

The generally accepted concept of cooling tower performance was developed by Merkel F., in 1925. A number of assumptions were used to simplify the development of final governing equation for the process. They can be lised as

1. There is no reduction in the mass flow rate of water due to evaporation,
2. Enthalpy of a saturated mixture of air and water vapour is a measure of the enthalpy of any mixture having an equal wet bulb temperature,
3. Lewis number is a constant,
4. Each particle of water is surrounded by a film of air that is saturated with moisture at the temperature of the water.

Accuracy was sacrificed as a result, but modifications may be made in the direct application to minimize the resulting error. Merkel F., for the first time, utilized the Lewis relationship to combine the coefficients of sensible heat and mass transfer into a single overall heat transfer co-efficient based on enthalpy potential difference as the driving force in the cooling tower. The governing equations were developed considering Heat and Mass transfer process taking place together.

In 1939, Colburn A.P., made an attempt in determining tower characteristics. In 1943, Lichtenstein J., handled the basic equations in a slightly different manner, and also produced a method of plotting the Number of Transfer Units and Tower Characteristics to facilitate the tower selection. At the same time, Hutchison W.K., and Spirey E., established a non-dimensional treatment for cooling towers problems.

Mickley H.S., in 1949, developed a more rigerous analysis considering temperature and humidity gradients, heat and mass transfer coefficients from water to film, and from film to air. Eventhough the process involved in a cooling tower is necessarily complex, the analysis offered by Mickley provides offers a possible means of evaluating the given cooling tower. The difficulty lies in obtaining the test data necessary to evaluate them.

During the same years Colburn A.P., and King W.J., showed that the effect of the hot water temperature is a function of the deck geometry and spacing. At first they found a conventional way of representing heat transfer for the tower in the form of plot against the air pressure drop which occurs during the process. They found that for a given air rate and tube diameter, the relationship was nearly linear. Kays W.M., and London A.L., made tests on finned tubes and correlated relative heat transfer with a friction-power constant. More recently Kelly N.W., and Swenson L.K., were able to evaluate emperical equations relating to tower performance with air pressure drop.

In 1950, Wood B., and Betts P., outlined a mathematical and graphical synthesis for natural draught towers, leading Chilton H., to determine some generalised simplifications in ascertaining the performance of such towers. Chilton examined the natural draught towers in detail for values of m_a/m_w varying from 0.5 to 1.5 for particular approaches and wet bulb temperatures, and showed that under usual operating conditions, Merkel's approximate solution will give a result close to results obtained by accurate integration with cooling ranges of 5°C to 10°C. In 1955, Margen P.H., established some very ingenious relationships between friction and heat transfer applicable to both Mechanical

and Natural draught water cooling towers. At the same time work was carried out comparatively independently along other lines, mainly with a view to obtain more efficient packings and more suitable heat transmission devices by Koch W., Mulder T.J.C., Otte W., and Velut J.

In 1950, a Cooling Tower Institute was established which is a non-profit, self-governing technical association dedicated to improvement in technology, design, performance and maintenance of cooling towers. Prevention of water and air pollution are the prime concern of the institute.

1.4 Technical Aspects in Cooling Tower Design [12, 15, 16, 29, 32]

Design of a cooling tower is quite complex . It is developed through a series of steps that consider the inter-relationship of many components and parameters like:

1. Selection of a proper cooling tower size,
2. The calculation of a required air flow rate,
3. Static pressure imposed by the tower,
4. External environmental factors which affect the air entering the tower,
5. Variation in requirement of the industry,
6. Optimum cooling tower design conditions.

It requires many tables, charts and correlations based on analytical as well as experimental data to predict the design quantities. Unfortunately, there is no single, simple meter, gauge or other mechanical device available to measure the capacity of a cooling tower. Testing a cooling tower can be a relatively simple task, but since it is seldom possible to test a tower at the design condition. The purchaser wants all the equipments that comprise plant investment completely with specific standards and capacity.

Owners, and their system designers, quite naturally want a cooling tower to perform a specific duty as predicted. Therefore, a systematic analysis of imposed heat load; the preferred water flow rate; the required cold water temperature; and a design wet bulb temperature etc., are essential. Similarly, manufacturers want full-rated performance from the cooling tower designers in order to compete with the market.

Design conditions are specified for the particular requirements before a cooling tower is purchased in order to get rid of inadequacy of the cool water temperature or volume. During operation all the cooling towers are expected to function at 100% of their capacity at the designed conditions. In actual

usage, the same may not be true due to

1. Slippage due to usage and defective maintenance might have reduced the performance efficiency of the tower over years of operation.
2. The installation would have been originally undersized or the present service being greater than the original requirements for which the tower was purchased.
3. New plant may need additional water and possibly colder temperature.

Thus a thorough study of a cooling tower becomes necessary, especially in large industrial installations such as electric power plants, nuclear stations, chemical plants, steam generating plants, oil refineries, refrigeration etc. in which cooling tower size and performance are closely integrated with the size and cost of other system equipments.

1.5 Present Work [25]

The present analysis follows a finite element technique for solution of governing equations using mass and heat transfer. The computations are carried out for the following cases:-

1. Exit state of water for the given cooling tower characteristic,

2. for a gi tower volume

3. the determination of tower characteristics.

The study has been mainly concentrated on cross-flow tower with partial attention to counter-flow towers.

In the analysis of cross-flow cooling towers finite element technique [8] is made use of . The governing differential equations [10] used in this analysis are derived considering heat and mass transfer together, with the tower volume as the control volume. An iterative scheme is developed in predecting the required outlet conditions of cold water with variable parameters.

Before starting an iterative scheme with the help of DEC-10 computer system, computations were carried out to find the permissible number of rows and columns, to save the computation time which is quite valuable.

The computer program [4, 9, 20, 22, 25, 27, 31] is made as general as possible with a wider flexibility in selecting range, approach, volume of tower, type of fill used, water loading and face velocity of air. Studies are made covering all the practical range of each parameter. For a required outlet condition the minimum size of tower, number of fills, velocity of air etc., were computed for a set of inlet conditions. Later the program was extended to findout whether the selected size is quite

sufficient or not. To start with a set of dimensions are selected for the tower and the volume required for the given inlet and required outlet conditions, is calculated based on the mass of water evaporated on the enthalpy separately. Finally comparison is made about the selection of dimensions.

Comparative performance and pressure drop characteristics have been carried out. For this purpose the dimensionless numbers known as " Number of Transfer Units" and " Tower Characteristics" were determined and studied for the specific tower under consideration.

Finally economical aspects [28] are delt with. As the data availability were extremely difficult a flexible program has been developed. Some results have been found for the available data.

CHAPTER 2

THEORY OF COOLING TOWERS

2.1 Operating Principles [13, 14, 19]

Cooling tower operation is mainly based on evaporative consideration and exchange of sensible heat. The mixing of two fluid streams at different temperature releases enthalpy of vaporization, causing a cooling effect to the warmer fluid. Thousands of years ago water, on this principle, was cooled in the porous earthen pots and now-a-days in canvas water bags.

In evaporative cooling three processes take place simultaneously,

1. transfer of heat by convection of sensible heat from warm water to cooler air,
2. due to mass transfer in the form of water molecules, because the main body of the air is at a lower vapour pressure than that of the water surface,
3. due to transfer of heat from the bulk of the liquid to the surface.

Among these three processes, effect of third process is negligible, since the thermal resistance to such direct internal conduction is very less. The evaporation on the convex surface of a drop is so intense that it can take place even in an atmosphere damp enough for condensation to occur on nearby objects. On the other hand, the vapour resulting from evaporation of the water has a low specific weight and contributes to the draught. This effect is known as "Thomson effect" [14].

In a cooling tower operation, sensible heat also plays an important role. Sensible heat, defined as heat that changes temperature, is also part of the cooling process, because when water is warmer than air in addition to evaporation air cools the water and its temperature rises as it gains the sensible heat of the water. Thus transfer of sensible heat from water to air takes places. On an average 75% of total heat is removed by evaporation and 25% by sensible heat transfer. In simple terms, a cooling tower is a simple air-mass heat exchanger that transfers heat from one mass to another.

2.2 Cooling Tower Terminology [1, 13, 14, 19, 32]

2.2.1 Ambient Wet-Bulb Temperature (T_2): Temperature to which air can be cooled, making it adiabatic to saturation by the addition of water vapour.

2.2.2 Approach (DESTAV-T_2) It is the difference between the outlet water temperature from the tower and the ambient air wet-bulb temperature.

2.2.3 Blow Down: The continuous (Fig. 2.1.a) or intermittent (Fig. 2.1.b) removal of a part of water from basin in order to maintain concentration of salt and other impurities as described below

Blow Down = 100 x (permitted chlorides in the make up water/permitted chlorides in the circulating water)

2.2.4 Capacity: The average amount of water circulating in the cooling system per unit time.

2.2.5 Cooling Factor (m_w/m_a): It is the ratio of mass of water entering the tower per unit time to the amount of dry air per unit time passing through the tower.

2.2.6 Cooling Range(T_3-DESTAV): It is the temperature difference between the inlet hot water to tower and outlet water from tower. The maximum attainable cooling range in cooling tower is temperature difference between the inlet hot water to tower and wet-bulb temperature of ambient air (T_3-T_2).

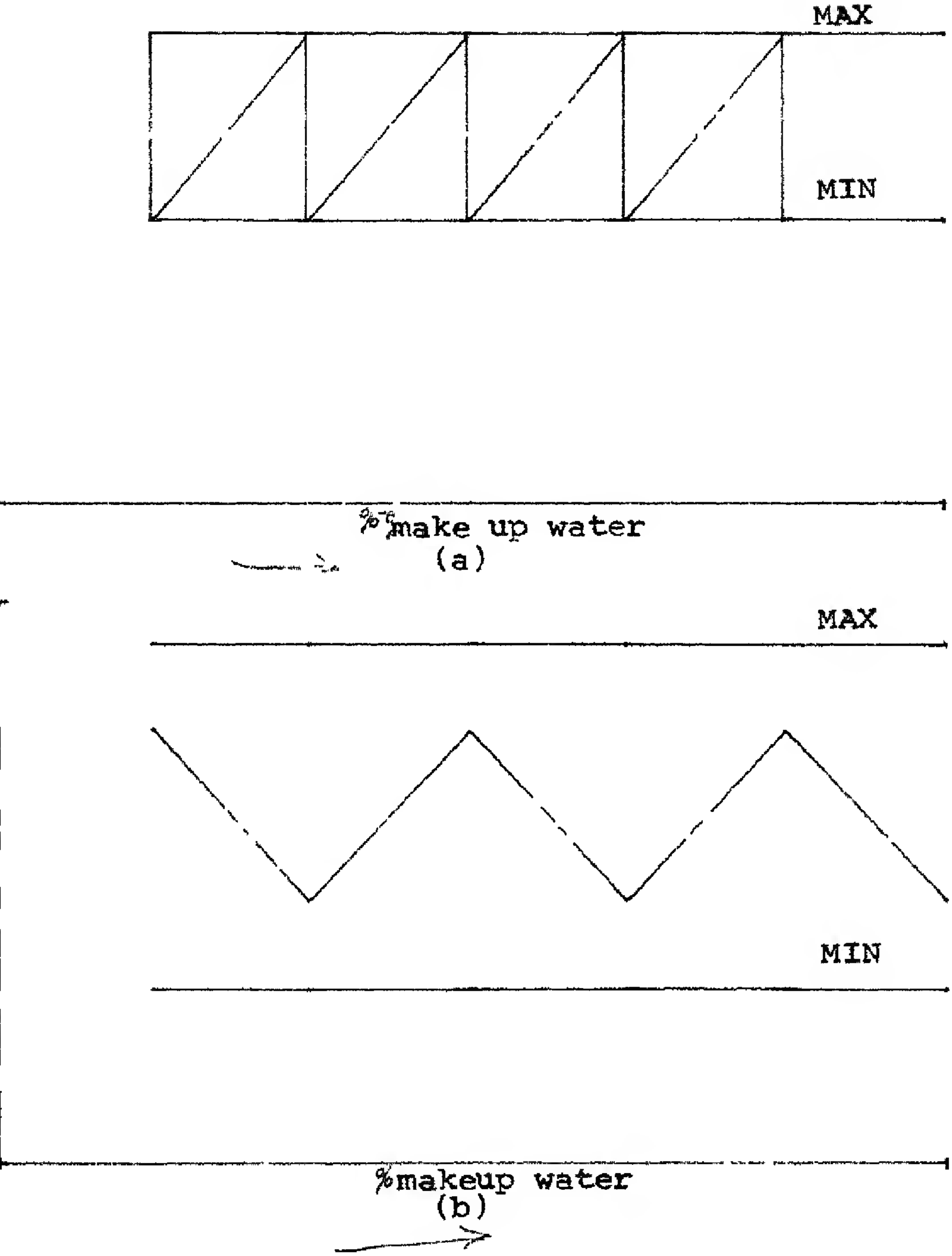


Fig 2.1.a Intermittent blow down

2.1.b Continueus blow down

2.2.7 Counter-Flow A system in which one fluid flows opposite to the other (i.e., their flow velocities are 180° apart). In cooling tower air comes into contact with hot water at 180° angle, air enters near the base of the tower and moves upward through the fill and falling water.

2.2.8 Cross-Flow: A system in which one fluid flows at 90° to the other flowing fluid. In cooling tower the air enters through the entire side wall and moves horizontally through the fill and falling water.

2.2.9 Cycles of Concentration: It compares dissolved solids in make up with solids in the circulating water. Since chlorides are soluble, cycles of concentration is equal to ratio of chlorides in circulating water to chlorides in make up and can be expressed as reciprocal of 'Blow Down'.

2.2.10 Drift Eliminator: Baffling arrangement provided after the tower fills with a view to eliminate out going hot air associated with water droplets to change direction few times. Droplets hit the eliminator surface and fall back into the tower.

2.2.11 Drift, Windage or-Carryover Loss The amount of water that is carried away from cooling tower by air in the form of mist in the process of cooling. It is expressed as % of water circulated.

2.2.12 Evaporation Rate: The rate at which water is being evaporated to cool the circulating water. The heat of evaporation is furnished by the cooling of the circulating water.

2.2.13 Fill Packing. Specially designed baffling used to provide a large contact surface between hot water and air.

2.2.14 Fog: A mist formed where the ambient air cannot absorb all the plumes moisture.

2.2.15 Forced Draught: Air introduced at the bottom of the tower is forced to the top by blower (usually centrifugal or radial).

2.2.16 Heat Load: The amount of heat (kJ/s) dissipated in a cooling tower expressed as product of water load and range i.e.,

$$\text{Heat load} = m_w * c_{p_w} * (T_3\text{-DESTAV})$$

2.2.17 Induced Draught: Air mover, usually an axial fan, on top of tower sucks air through the fill and discharges it out of the tower.

2.2.18 Louvers Baffles used for changing the direction of air flow through a tower in a uniform, parallel manner and preventing water droplets from splashing out of tower as they fall through the structure.

2.2.19 Make Up Water: The amount of water required to replace normal system losses caused by evaporation, drift, blowdown and small leakages.

2.2.20 Plume: Visible manifestation of water vapour leaving the tower.

2.2.21 Retention Time: The time required for water to fall from the distribution header to the cooling tower basin.

2.2.22 Water Load ($\dot{m}_w$): Water circulation rate over the tower expressed in terms of mass per unit time.

2.3 Classification of Cooling Towers [1, 2, 13, 19, 21, 30]

Most cooling towers perform the same function as an automobile radiator, transfer heat from warm circulating water to atmosphere. However, in the former the hot water and ambient air comes in direct contact during the course of heat transfer. As such they are known as WET TOWERS. They can be classified as follows

1. Based on method of air introduction to the tower or type of flow,
   - i. cross flow
   - ii. counter flow
   - iii. cocurrent flow
2. Method of heat dissipation.
   - i. wet cooling
   - ii. dry cooling
   - iii. wet-dry cooling
3. Based on application,
   - i. industrial
   - ii. power plant

The principal type of towers under first classification can be written as:

1.	Ponds	i.	natural cooling pond
		ii.	spray cooling pond
2.	Natural draft	i.	spray filled
		ii.	splash filled
		iii.	hyperbolic towers
3.	Mechanical draft	i.	forced draft
		ii.	induced draft

The various types of towers can be compared in term of flow area occupied for the same amount of heat removal and is as shown in Table 2.1.

TABLE 2.1

COMPARISON OF THE TOWERS FLOOR AREAS FOR THE SAME HEAT LOAD

TYPE OF TOWER	RELATIVE FLOOR AREA OCCUPIED
NATURAL COOLING POND	1000
SPRAY POND	50
SPRAY FILLED ATMOSPHERIC TOWER	15
SPLASH FILLED ATMOSPHERIC TOWER	4
MECHANICAL DRAFT COUNTER FLOW TOWER	1.5
MECHANICAL DRAFT CROSS FLOW TOWER	1.2 to 2

2.3.1.a Natural Cooling Pond:

Both artificial and natural water reservoirs are used as cooling ponds. The warm process water is introduced at one end and a cooled water is withdrawn from the opposite end, in order to avoid short circuiting of warm water. To achieve best results, the total area of the water surface should be as large as possible. Two or more ponds can be used together to transfer a large quantity of heat . To increase the heat dissipation the ponds are constructed below earth surface.

Advantages:

1. Less initial investment cost,
2. Low maintenance cost,
3. Longer life,
4. Doesnot require make-up water for a long period.

Disadvantages:

1. Its heat removal capaicty is very low (70 kJ/m^2 of surface area-hr-°C)
2. Special attention is required in order to prevent detritus entering the pond and growth of water vegetation,
3. Larger surface area for the ponds cause serious problem in industrial cities,

4. Effect of solar radiation during summer affects the upper water layer and its temperature will be higher than the temperature of water at certain depth, leading to serious problem in selecting position of cooled water outlet.

2.3.1.b Spray Pond:

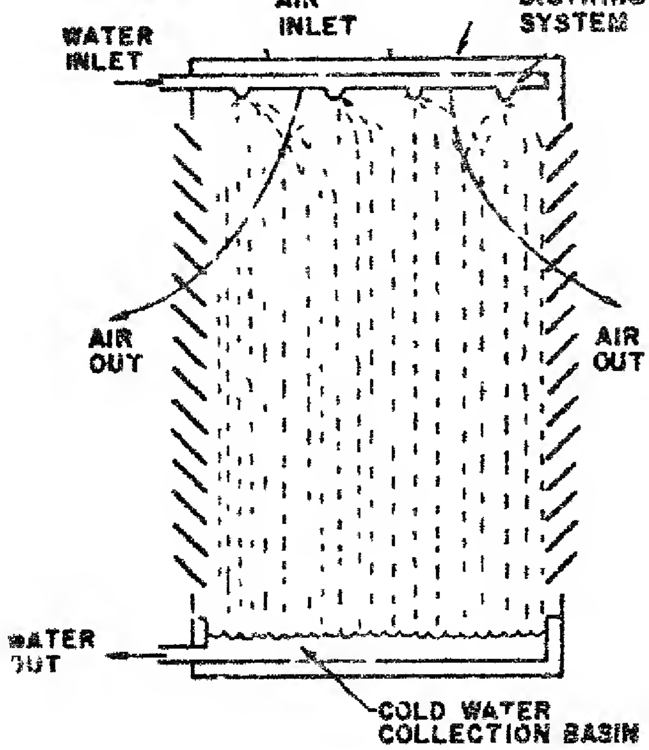
It differs from the natural cooling ponds because the hot water is carried to a height of 2-3 meters over the basin and sprayed through a spray system consisting of a network of distribution pipes fitted with spray nozzles. In some cases the distribution nozzles sprays water vertically from the surface of the water in the pond. Water cools as air mixes with the spray and evaporates some of it. Air movement depends on atmospheric conditions and the aspiring effects of the spray nozzles. These types of ponds are built at a site which is open to wind from all directions. They are usually situated at a distance from buildings and roads to avoid nuisance to inhabitants because of the formation of fog.

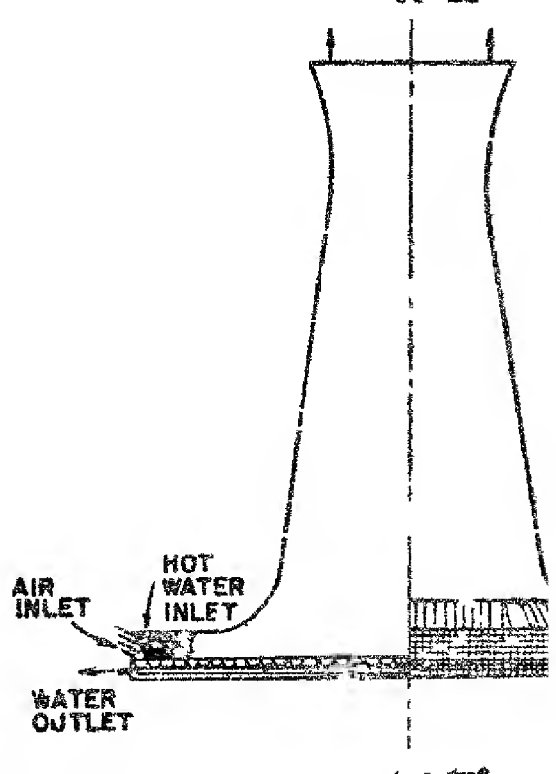
Disadvantages: 1. Performance is limited by relatively short contact time of air and water spray,

2. In absence of louvers and fine spray more drift losses occur calling for more make-up water,
3. Height of spray is limited due to pump energy requirement,
4. Collection of dust and impurities due to the open surface to atmosphere leads to more maintenance cost,
5. Causes considerable environmental nuisance,
6. Although spray tanks are more compact in design and better in their performance than natural ponds, they still require larger area and have limited performance capacity.

2.3.2.a Natural Draft, Spray-Filled Tower [Fig. 2.2]

The spray-filled tower is essentially a compact enclosure having louvers on all sides to prevent drift losses, and tank at the bottom. Water which is sprayed downwards though nozzles, comes into contact with air flowing cross-wise as wind normally blows horizontally and gets cooled. The main components are spray system, water basin and louvers. The nozzles plays an important role on the tower efficiency. The dense spray improves the efficiency and confined spray cuts the water loss.


INLET
SYSTEM
WATER
INLET
AIR
OUT
AIR
OUT
WATER
OUT
COLD WATER
COLLECTION BASIN


HOT
WATER
INLET
AIR
INLET
WATER
OUTLET

To ensure a uniform distribution of water and to reduce drift losses, low output nozzles pointing downwards are used.

Advantages:

1. Light weight and small in size. The smaller space requirement enables its installation even on the roof of a building,
2. Easy operation and maintenance,
3. Requires very less power (only to pump water for spray),
4. The hot air doesnot mix with fresh air,
5. Life is trouble free and long as not many mechanical parts are involved,
6. Since louvers are always wet, they increase water surface exposed to air.

Disadvantages:

1. Cooling range is limited,
2. Efficiency is low because of limited contact time and the wind losses. Not suitable for big industrial units,
3. Water is sprayed from top, requiring more pump power,
4. Nozzles may get clogged, requiring cleaning to avoid unbalanced water spray,

5. More pumping pressure - for atomization of water in a nozzle.

2.3.2.b Splash-Filled Natural Draft Tower:

Filling is incorporated to increase water break-up with a view to provide additional water surface to air flow apart from spray filled towers. Open louvers allow outside air to pass through tower over its full height. Despite the greater cooling efficiency than spray-filled towers, it is rarely used now-a-days because of increased initial cost and maintenance.

Disadvantage:

1. Greater length of tower is needed to compensate for the narrow structure,
2. Initial cost and pumping head are high,
3. Tower's extreme length and height and narrow width necessitates good anchoring to withstand high winds.

2.3.2.c. Hyperbolic Towers [Fig. 2.3]

These towers are suitable for the largest heat load applications. They are built as cross flow or counter flow depending on requirement. They have a tall cylindrical structure above the spray system to provide chimney effect, the natural-draught. This draught,

The higher initial investment is balanced against savings in fan cost, fan power, longer life and less maintenance. They find their preferences as under:

1. Where geography dictates maximum height release of moist air plumes,
2. For confined, restricted area sites,
3. Where extremely high power cost make natural draft most applicable.

The hyperbolic shape of the tower is employed from the aerodynamic and practical view points, but it does not have any thermodynamic significance. The reasons for the preference of the hyperbolic shape are:

1. The cross section at the bottom, provides more space for fill and reduction in height of louvers, leading to reduction in pumping head.
2. The direction of inlet air changes from horizontal to vertical smoothly. Thus the turbulence is minimised.
3. The wind load on the structure is low due to reduced cross section at the top, where wind velocities are high.
4. Because of 'doubly curved' nature it is structurally strong as bending stresses are negligible.

5. Some what enlarged top decreases the velocity of air comparatively. The water particles in drift will be condensed due to sudden change in velocity.

Advantages:
1. Simplicity in operation due to absence of mechanical parts,
2. Total avoidance of heated air recirculation,
3. High heat dissipation capacity,
4. Absence of fan,
5. Can be located at the middle of structural buildings as there is no ground fogging due to large height of the tower,
6. Loss of water due to drfft is negligible,
7. Longer life.

Disadvantage:
1. High initial cost,
2. No control over air supply hence on outlet temperature of water.

2.3.3.a. Mechanical-Forced Draft Towers [Fig. 2.4]:

The forced draught created by the fan mounted at he bottom of the tower eliminates the dependence of cooling on the wind velocity and can be controlled as per requirement. The system becomes very compact for a given heat load.

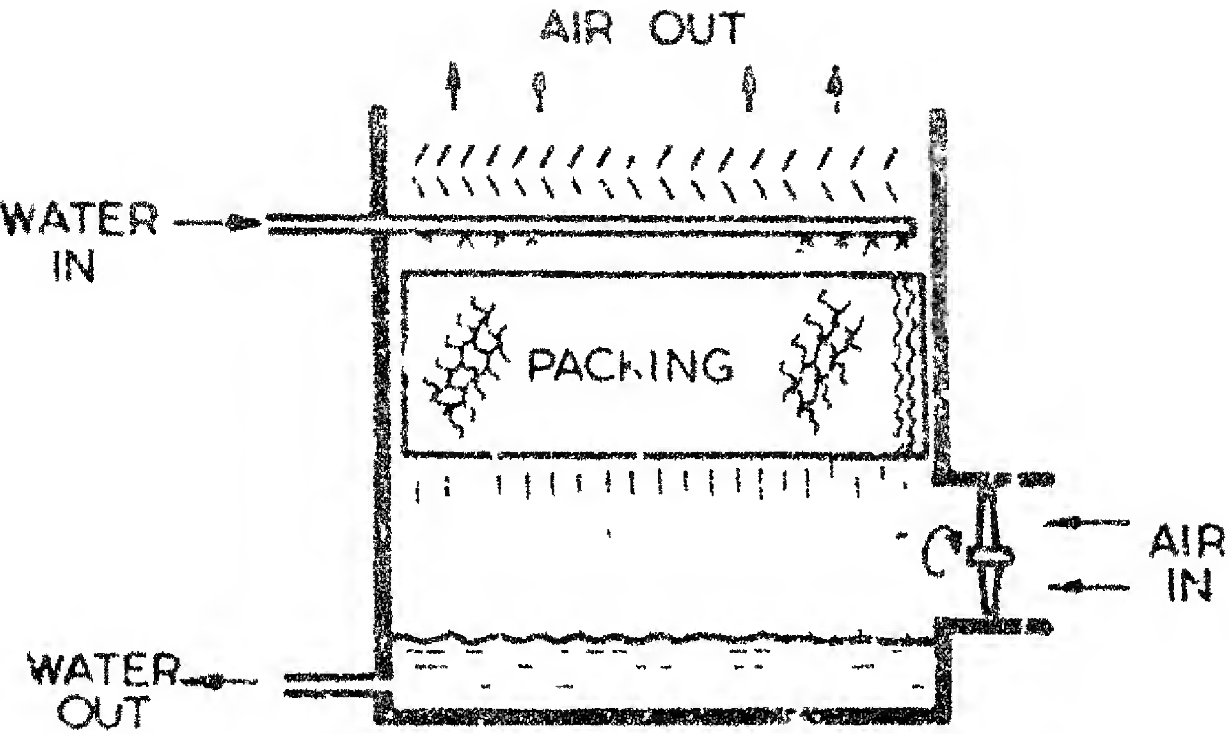


Fig 2.4 Mechanical dreft tower

Advantage:

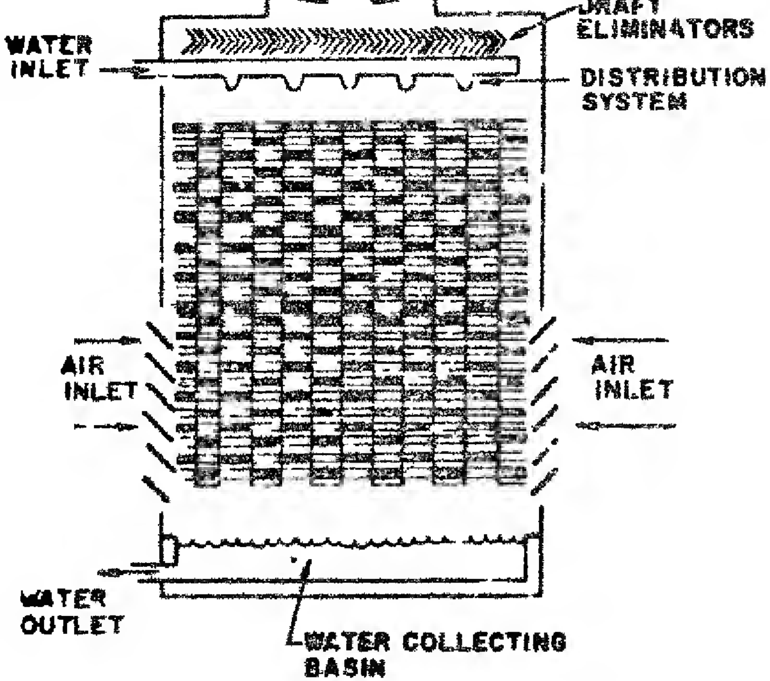
1. Requires less space and piping than atmospheric towers,
2. Cooling efficiency is improved,
3. Close control of cold water temperature is possible,
4. Fans mounted on the floor, better foundation-less vibration,
5. Part of the velocity head is converted into pressure head and at the upper part again into velocity head, thus requiring less power,
6. Tower is compact and more packing is possible in a given volume,
7. Fan is not subjected to moist conditions.

Disadvantage:

1. Operation of tower depends on fan characteristics,
2. Limited fan size and more energy for fan,
3. Higher operating and maintenance cost,
4. Possibility of recirculation of hot humid air.

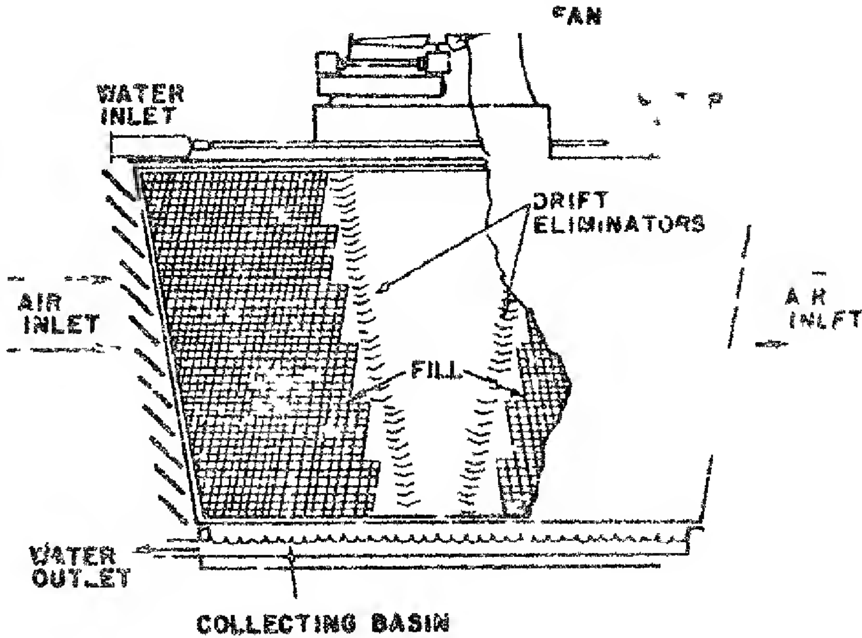
2.3.3.b. Induced Draft Tower [Figs.2.5.a and 2.5.b]

The fan is mounted on the top of the tower, hot and humid air is pumped out of the tower creating draft



Counterflow tower

Fig 2.5.a



Crossflow tower

Fig 2.5.b

It is of two types

i. Counter flow,

ii. Cross flow.

Maximum performance is achieved in induced draft counter flow tower because coldest water comes into contact with the driest air and viceversa, thereby having the maximum enthalpy gradient. In cross flow due to fill in a ring outside the tower requires lower water pumping head than in the counter flow.

Disadvantage: [Counter Flow]

1. More air resistance and uneven air distribution of air inside the tower leads to larger fan power,
2. Limited water loading and high pumping head,
3. Blower is subjected to hot and highly moistened air,
4. High maintenance cost,
5. Hot water distribution system is not easily accessible for cleaning,
6. More stronger structure is required at the top to reduce vibration,
7. The power transmission system increases cost and maintenance.

Advantage [Cross Flow]

1. Low static pressure drop and low pumping head,
2. More filling is possible per unit volume,
3. Larger diameter of fans implies less number of cells.

Disadvantage:

1. Design is complex,
2. Low pressure on water distribution system doesnot give fine spray,
3. Algae growth is encouraged, as water at top is exposed to atmosphere.

2.4 Main Components of Cooling Tower

2.4.1 Fill Material [17, 19]:

The cooling tower packing material is used to render as large air-water interfacial area as possible with limited air-pressure losses. The falling water on fills spreads in such a way as to provide a large surface area of contact between water and air stream. Inspite of present wide-spread and continually growing use of cooling towers, only limited information is available on the specific performance and pressure drop characteristics of cooling tower packing arrangements.

There are basically two types of packing-splash and nonsplash arrangements. The former utilise a system of laths generally of wood, variously shaped and spaced,

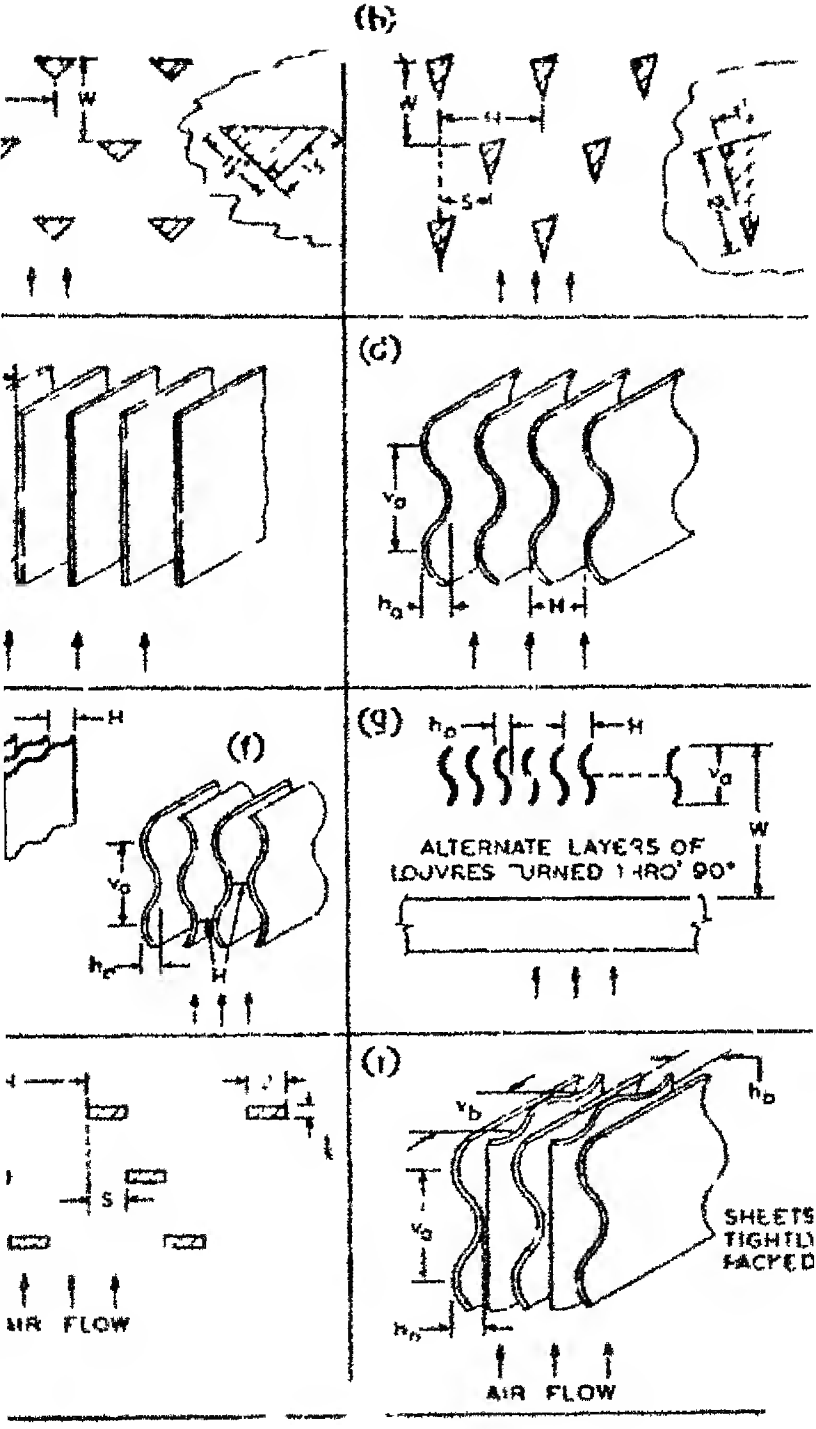
for the falling water to break into droplets. In the later case, drops are discouraged, and the water is caused to spread thinly over the surface of the filling. Splash type fill are generally used in cross flow designs and non-splash (film) type are utilized in counter flow designs.

Packings can be made from a variety of materials including wooden or plastic laths, corrugated asbestos cement sheets, plastic sheets, sheets of galvanized steel, resin-impregnated paper or glass fibre [Fig. 2.6]. The factors influencing the choice of fill are heat transfer characteristics, pressure loss, total packing cost and durability which implies freedom from maintenance. Naturally a fill that has lowest cost, higher heat transfer and low pressure loss is preferred. However, the problem of selection becomes more difficult when a packing is better in one or two respects and worse in the remainder.

2.4.2 Distribution System [14, 19]:

The function of distribution system is same as that of fill. Here inlet hot water is distributed uniformly over the fill section. It is of two types, gravity and spray types.

In gravity type a shallow tank or channels open to atmosphere are located on the top of the tower. Water



2.6 Types of packing used in towers

falls through the orifices over the tower packing due to gravity providing splash type pattern

In spray type, a header having a set of nozzles issues fine spray of water being distributed evenly over the fill. We can consider other types also in which the water is spread in a form of a thin film on the packing underneath without formation of droplets (film type).

2.4.3 Circulating Pumps [14, 19]

Pumps are used to circulate hot water over top of the tower and to distribute cold water from tower to the process where its service is required. They may be of different types. The centrifugal pumps (single or multi-stage) are most commonly used. Their selection depends upon:

a. discharge, b. head to be produced,
c. efficiency, d. source of power,
e. installation, f, maintenance,
g. impurities in water, etc.

2.4.4 Fans [14, 19]:

Fans handle large volume of air at low velocities with a low-pressure drop through the tower. Thus the fan should be economically designed to handle desired air flow at minimum input.

In induced dr ft towers s the fans are mounted on the top of the tower they are subjected to moistened conditions. Thus the blades should be given a proper protective coating. The most popular protective coating is not dipped galvanizing. Danger from excessive vibration, both to tower and equipment must be taken care with safety device. A large decrease in efficiency results when a thin layer of dirt or ice is formed on the fan blades. A 1/3 mm thick coating may reduce 4 to 5% efficiency of fan. Even the clearance between the blade tips and fan housing has an important effect on efficiency. Thus a careful design of fan is needed.

2.4.5 Fan Drives, Speed Reducers and Motors:

These are the accessories to fan. The prime function of fan drive or drive shaft is to transmit power from the prime mover i.e., motor to the gear or speed reducer. Special care has to be taken in design of these parts as because they are also operating under the same condition as that of fan. This has a direct effect on the efficiency of the fan.

CHAPTER - 3

MATHEMATICAL ANALYSIS

3.1 Psychometry and Heat Transfer [9, 10, 17, 24]

The determination of cooling tower performance requires the study of moist air i.e. psychometry and heat transfer relations. The expressions for various quantities used in the present investigation have been given below.

1. Humidity ratio for unsaturated air is expressed in terms of mol-fraction of water:

$$w = 0.622\, x_w/(1 - x_w) \tag{3.1.1}$$

2. Humidity ratio for saturated air:

$$w_s = 0.622\, f_s\, p_{w,s}/(p - f_s\, p_{w,s}) \tag{3.1.2}$$

where f_s has been functionally related to T from the data as

$$f_s(T) = 1.004505 - 2.0707 \times 10^{-5}\, T + 9.1415 \times 10^{-7} T^2$$

3. Enthalpy

$$h = c_{pa,w}\, t + 2501.4\, w \tag{3.1.3}$$

where $c_{pa,w} = c_{pa} + 1.884\, w$

4. Prandtl number

$$Pr \quad c_{pa}\,\mu/k \qquad (3.1.4)$$

5. Reynolds number

$$Re = \rho\, V\, L\, /\, \mu \qquad (3.1.5)$$

6. Heat transfer coefficient

$$h_c = \frac{0.171\; k\; Pr}{d_e^{\,0.22}} \left(\frac{VSEC}{\nu}\right)^{0.78} \qquad (3.1.6)$$

7. Properties of air and water in terms of temperature

i $$P_{w,s} = 225.65 \times 10^{-4} \times 9.81/[(7.21379 + (1.152 \times 10^{-4} - 4.787 \times 10^{-9}\; t)(t - 483.16)^2)\;(647.31/t-1)]$$

ii $$c_{pa} = 0.219 + 0.0343 \times 10^{-4}\; TR - 0.297 \times 10^{-8}\; TR^2$$

iii $$c_{pw} = 4.2097187 - 1.4125 \times 10^{-3}\; T + 1.375 \times 10^{-5} T^2$$

iv $$h_{fg} = 597.34 - 0.555\; T$$

$$0.2389 \times 10^{(5.1463\; -\; 1540/\; t)}$$

v $$h_f = 0.99615\; T + 1.8239 \times 10^{-6}\; T^2 - 0.13468 \times 10^{(-0.036\; T)} + 0.13468$$

vi $$\rho_a = 1.291 - 4.525 \times 10^{-3}\; T + 1.125 \times 10^{-5}\; T^2$$

vii $$\mu = 0.0207 + 8.5 \times 10^{-5}\; T + 1.625 \times 10^{-5}\; T^2$$

viii $$\nu = 1.325 \times 10^{-5} + 8.525 \times 10^{-8}\; T + 1.625 \times 10^{-10}\; T^2$$

Governi   ations [4, 6, 10, 14]

These governing equations based on the heat and mass transfer principles help analyse the given tower. The following assumptions are made·

1. no water losses except evaporation,
2. no heat transfer through the walls of the tower.

They are used to get the condition on the psychometric chart, representing the changes in the state of moist air passing through the tower. The rate of evaporation depends upon the

1. molecular weight of the liquid,
2. velocity of the impressed draught,
3. relative saturation and partial vapour pressures i.e. inference upon the humidity of the circulating air,
4. surface exposed to evaporation.

3.2 Cross-Flow Analysis [10, 25]

In this case the air and water flows are perpendicular to each other. Water falls from top of the tower and air flows from outerside of the tower. The analysis of this type is extremely involved. Because the direction of air flow will be changing constantly due to falling water droplets and packing arrangement inside the tower.

The resistance to flow of air increases thus leading pressure drop which is difficult to predict. Hence a a whole the exact nature of flow is difficult to anal in case of cross-flow. Analysis is again done using finite element technique. The errors committed by the assumptions are minimized by selecting large number o grids. Figure 2.5.b shows a typical cross-flow cooli tower having fills and grids.

Figure 3.1 shows the element (i, j) of cross flow cooling tower under consideration for analysis w control volume (indicated by dotted lines).

$$\dot{m}_{w_{i+1,j}} = \dot{m}_{w_{i,j}} - \dot{m}_{a_{i,j}} (w_{i,j+1} - w_{i,j}) \quad (a)$$

$$T_{w_{i+1,j}} = T_{w_{i,j}} - \Delta T_{w_{i,j}} \quad (b)$$

$$h_{i,j+1} = h_{i,j} + \Delta h_{i,j} \quad (c)$$

By heat balance

$$\text{Heat gained by air} = \dot{m}_{a_{i,j}} (h_{i,j+1} - h_{i,j})$$

$$\text{Heat lost by water} = \dot{m}_{w_{i,j}} c_{pw} T_{w_{i,j}} - (\dot{m}_{w_{i}}$$

$$\dot{m}_{a_{i,j}} (w_{i,j+1} - w_{i,j}) c_{pw} T_{i+1,j})$$

Using Eq. (3.2.1.c), Eq. 3.2.3 reduces to

$$d\dot{Q} = \dot{m}_{a_{i,j}} (w_{i,j+1} - w_{i,j}) c_{pw} T_{w_{i,j}} + [(\dot{m}_{w_{i,j}}$$

$$\dot{m}_{a_{i,j}} (w_{i,j+1} - w_{i,j}) c_{pw} \Delta T_{w_{i,j}}] \quad (3.$$

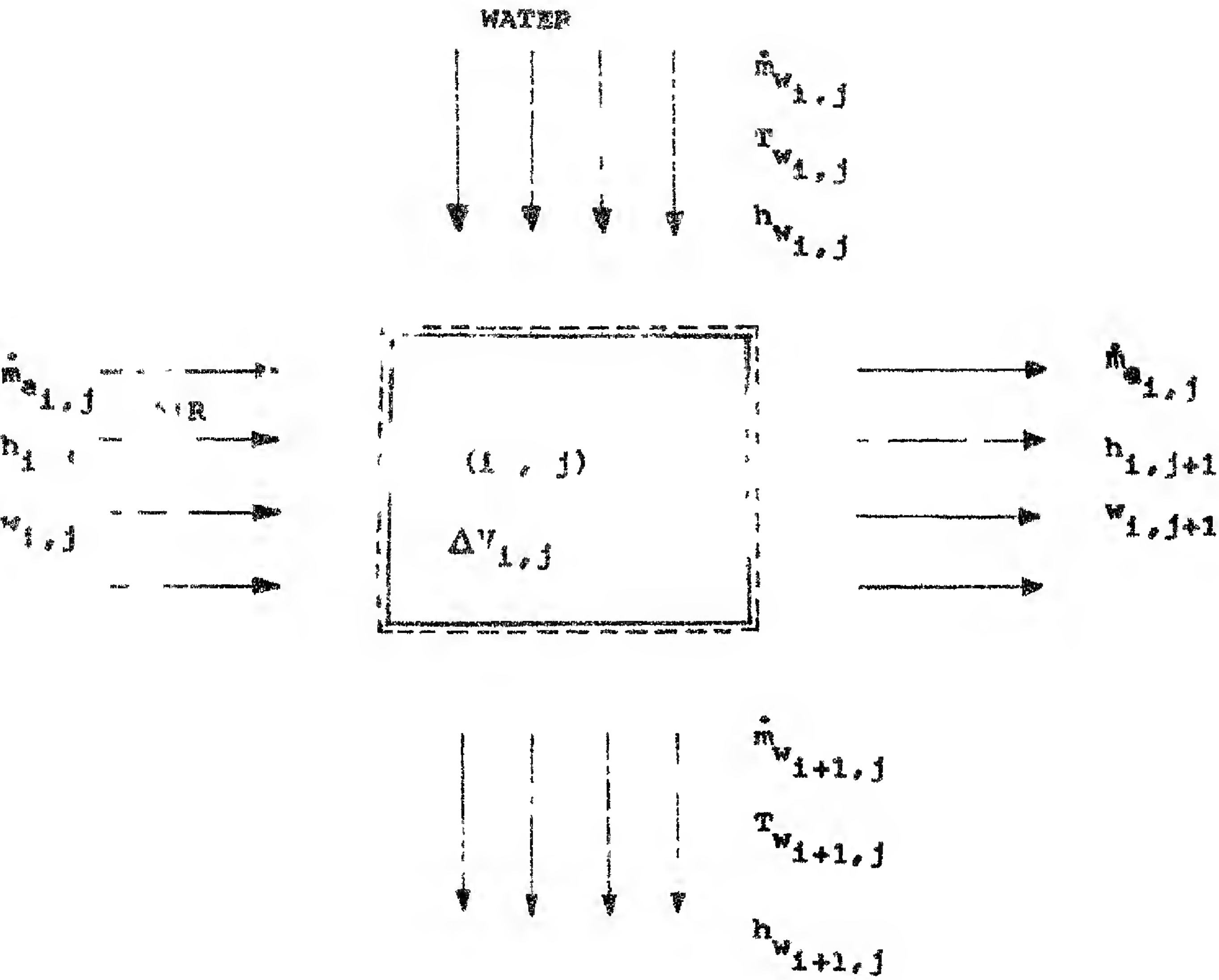


Fig. 3.1 ELEMENT (i,j) IN CROSS-FLOW WITH CONTROL VOLUME

But heat gained by air Heat lost by water

$$dQ = \dot{m}_{a_{i,j}} (w_{i,j+1} - w_{i,j}) c_{pw} T_{w_{i,j}} + [\dot{m}_{w_{i,j}} c_{pw} \Delta T_{w_{i,j}}] - \dot{m}_{a_{i,j}} (w_{i,j+1} - w_{i,j}) c_{pw} \Delta T_{w_{i,j}} \quad \ldots \quad (3.2.5)$$

Also total heat transfer = Heat transfer due to convection + Heat transfer due to mass transfer

$$\dot{m}_{a_{i,j}} (h_{i,j+1} - h_{i,j}) = h_c A_v dv_{i,j} (T_{w_{i,j}} - T_{a_{i,j}}) + h_D A_v dv_{i,j} (w_s(T_{w_{i,j}}) - w_{i,j}) h_{fg}(T_{w_{i,j}}) \quad \ldots \quad (3.2.6)$$

By mass balance

$$\dot{m}_{a_{i,j}} (w_{i,j+1} - w_{i,j}) = h_D A_v dv_{i,j} (w_s(T_{w_{i,j}}) - w_{i,j}) \quad (3.2.7)$$

Rewriting Eq. (3.2.6)

$$- \dot{m}_{w_{i,j}} c_{pw} dT_{w_{i,j}} = h_D A_v dv_{i,j} [Le\, c_{pa} (T_{w_{i,j}} - T_{i,j}) + (w_s(T_{w_{i,j}}) - w_{i,j}) h_{fg}(T_{w_{i,j}})] \quad (3.2.8)$$

Combining Eqs. (3.2.5, 3.2.7 and 3.2.8) and neglecting smaller values

$$\frac{dh_{i,j}}{dw_{i,j}} = Le\, c_{pa} \frac{(T_{w_{i,j}} - T_{i,j})}{(w_s(T_{w_{i,j}}) - w_{i,j})} + h_g(T_{w_{i,j}}) \quad \ldots \quad (3.2.9)$$

Using the relations between enthalpy, temperature, specific heat and humidity, we can write

$$(h_{s(T_{w_{i,j}})} - h_{i,j}) = c_{pw} (T_{w_{i,j}} - T_{i,j}) + 2501.4$$

$$(w_{s(T_{w_{i,j}})} - w_{i,j}) \qquad (3.2.10)$$

Combining Eqs. (3.2.9 and 3.2.10)

$$\frac{dh_{i,j}}{dw_{i,j}} = Le \frac{(h_{s(T_{w_{i,j}})} - h_{i,j})}{(w_{s(T_{w_{i,j}})} - w_{i,j})} + h_{g(T_{w_{i,j}})} - 2501.4\, Le \quad .. \qquad (3.2.11)$$

Equation 3.2.11 gives the relation for the condition line of the heat and mass transfer process. It can be plotted on the psychometric chart after evaluation for a given set of operating conditions as shown in Fig. 3.2.

Rewriting Eq. (3.2.5),

$$dT_{w_{i,j}} = \frac{\dot{m}_{a_{i,j}} (dh_{i,j} - dw_{i,j} \; h_{f,w_{i,j}})}{(\dot{m}_{w_{i,j}} - \dot{m}_{a_{i,j}} \; dw_{i,j}) \; c_{pw}} \qquad (3.2.12)$$

$$dv_{i,j} = \frac{\dot{m}_{a_{i,j}}}{h_D \; A_v} \left[\frac{dw_{i,j}}{w_{s(T_{w_{i,j}})} - w_{i,j}} \right] \qquad (3.2.13)$$

Total volume can be written as:

$$V = \sum_{i=1}^{M} \left(\sum_{j=1}^{N} dv_{i,j} \right) = \int\!\!\int_{ij}^{MN} \frac{\dot{m}_{a_{i,j}}}{h_D \; A_v} \left(\frac{dw_{i,j}}{w_{s(T_{w_{i,j}})} - w_{i,j}} \right) \quad ... \qquad (3.2.14)$$

Equations (3.2.11, 3.2.12 and 3.2.14) forms the governing differential equations of cross flow tower analysis.

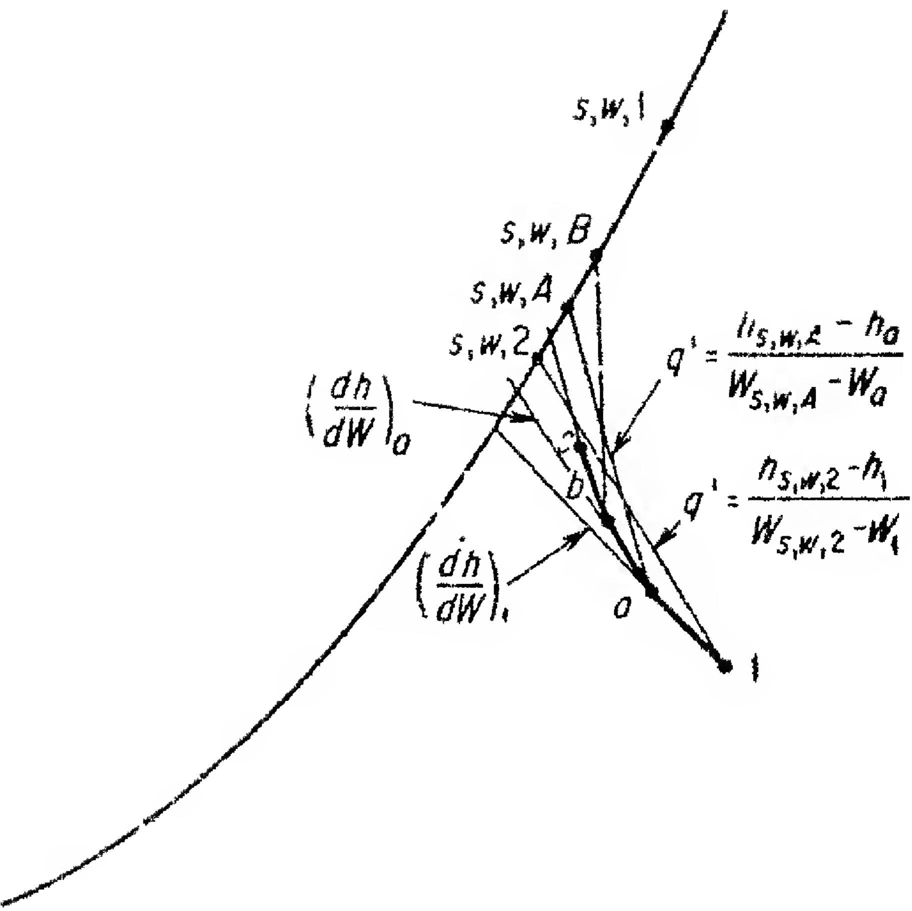


Fig 3.2 Condition line for cooling tower on psychometric chart

3.3 Counter-Flow Anal is

i. With evaporation loss

Water and air move in opposite directions parallel to each other. The whole tower is divided into number of sections for stepwise integration. In this case the flow is one dimensional. Proceeding in the similar way as in case of cross-flow analysis, we get the following governing equations:

$$\frac{dh}{dw} = Le \frac{(h_{s,w} - h)}{(w_{s,w} - w)} + (h_{g,w} - 2501.4\ Le) \qquad (3.3.1)$$

$$-\Delta t_w = \frac{\dot{m}_a}{\dot{m}_w\ c_{pw}} (\Delta h - \Delta w\ h_{f,w}) \qquad (3.3.2)$$

$$dv = \frac{\dot{m}_a}{h_D\ A_v} \left(\frac{dw}{w_{s,w} - w} \right) \qquad (3.3.3)$$

$$\text{Thus total volume } V = \int dv = \frac{\dot{m}_a}{h_D\ A_v} \int_{w_1}^{w_2} \left(\frac{dw}{w_{s,w} - w} \right) \qquad (3.3.4)$$

Eq. (3.3.1) gives the condition line on psychometric chart for various points in the tower. Equations (3.3.1, 3.3.2 and 3.3.4) will form the governing differential equations for the cooling porcess in the counter-flow tower.

ii. Without evaporation loss:

Here the analysis is similar as that of 3.3.i.

But the following changes are noted

a. $\dot{m}_{wo} = \dot{m}_{wi}$

b. $\dot{m}_a \; dh \quad - \dot{m}_{,} \; dh_{f,w}$

c. $\frac{dh}{dw} \quad Le \quad \frac{(h_{s,w} - h)}{\omega_{s,w} - \omega} \quad + (h_{fg,w} - 2501.4 \; Le)$

3.4 Tower Characteristic and Number of Transfer Unit [4, 6, 18]

The sensible and latent heat transfer are combined into an overall process based on enthalpy potential as driving force. An equivalent heat transfer coefficient has been chosen to represent the combined effects of heat and mass transfer coefficients. The basic equation based on heat transfer to air by water can be written as

$$\dot{m}_a \; dh = k_e \; A \; V(h_{s,w} - h) = \dot{m}_w \quad dT \tag{3.4.1}$$

Therefore, we can write

$$k_e \; A \; V/\dot{m}_a = \int dh/(h_{s,w} - h) \tag{3.4.2}$$

$$- k_e \; A \; V/\dot{m}_w = \int \; dT/(h_{s,w} - h) \tag{3.4.3}$$

The dimensionless number on the left hand side of Eqs. (3.4.2 and 3.4.3) are known as " NUMBER OF TRANSFER UNIT" and " TOWER CHARACTERISTICS" respectively. It is found that tower characteristic is less accurate than number of transfer units. Thus, in practice, the given tower is analysed based on Eq. (3.4.2).

3.5 Volume of Tower Based on Water Evaporation Rate [2, 10, 24, 31]

Equations (3.2.13and 3.3.3) give the volume at each element and the total volume of tower is given by

Eqs. (3.2.14 and 3.3.4) for cross flow and counter flow, respectively. For the cross-flow we calculate the volume based on mean values of humidity and humidity difference.

$$\text{i.e.} \quad V = \sum_{i=1}^{M} \left(\sum_{j=1}^{N} dv_{i,j} \right) = \int_{i}^{M} \int_{j}^{N} \frac{\dot{m}_{a_{i,j}}}{h_D A_V}$$

$$\left[\frac{(dw_{i,j} + dw_{i,j+1})}{4} (1/(w_{s(T_{w_{i,j}})} - w_{i,j}) + 1/(w_{s(T_{w_{i,j+1}})} - w_{i,j+1})) \right] \qquad (3.5.1)$$

3.6 Procedure of Solving Problems in Cooling Towers [10, 18, 24]

3.6.1 Cross-Flow:

The water inlet condition for all elements in first row and air inlet condition for all elements in first column are known. Thus, for the element (1,1) we know all the inlet conditions. Hence we can calculate the outlet conditions of air and water from Eqs. (3.2.11 and 3.2.12). As the motion of air and water are at 90° to each other the outlet condition of air will be inlet condition of air for element (1,2). Thus, for element (1,2) we know both air and water inlet conditions and we can carry out the analysis for all the elements in the first row. The Lewis number is calculated at an average condition.

The water temperatures at exit for each element of the first row are known from Eq. (3.2.12). For the second row computation is repeated. This method is followed until all the rows are completed giving exit state of water for each column. Further, volume of cooling tower is calculated using Eq. (3.2.14).

The average outlet condition of water is found from the following equation:

$$T_{w,av} = \sum_{j=1}^{N} T_{w_{M+1,j}} / N \tag{3.6.1}$$

Similarly, the average outlet condition of air at exit is given by

$$h_{a,av} = \sum_{i=1}^{M} h_{i,N+1} / M \tag{3.6.2}$$

$$w_{a,av} = \sum_{i=1}^{M} w_{i,N+1} / M \tag{3.6.3}$$

3.6.2 Counter Flow:

In this type of towers Eqs. (3.3.1, 3.3.2 and 3.3.4) forms the governing equations of the process, and are solved for the given inlet and desired exit conditions of water, which gives desired range. As flow rate remains the same throughout the tower the range is equally divided as the number of divisions of the tower. This forms the required change in water temperature (dT) at each stage.

For the determination of the size of the tower or the tower characteristics, a numerical method is applied by dividing it into a number of sections. Stepwise integration is carried out from the bottom of the tower until the exit state of air is determined. In this way for known values at various state points, the size of the cooling tower is determined using Eq. (3.4.2). Knowing all the values in Eq. (3.3.1), we can determine the value of dh/dw. Further, we know ΔT_w. Thus from Eqs. (3.3.1 and 3.1.14) we have two unknowns dh and dw, which can be solved. Thus the value at the exit of that division is calculated. And the analysis is continued until the exit values are calculated.

3.7 Variable Lewis Number [10, 23]

As stated earlier, it gives a relationship between heat transfer and mass transfer coefficients in a dimensionless form named after the discoverer, Prof. Lewis, W.K. (1922). Its value depends on the velocity of air flow, dry-and wet-bulb temperatures of air and water (inlet) temperature. It can be represented as

$$Le = f\,(V,\ T_{db},\ T_{wb},\ T_w) \qquad (3.7.1)$$

A generalized relation for Lewis number is given by:

$$F(VMIN) = 0.333(\log_{10} VMIN)^2 + 0.177046 \log_{10} VMIN + 2.6949 \times 10^{-3} \qquad (3.7.2)$$

$$GH \quad 4.32 \times 10^{-4} \quad (T_1 + T_w)/2 + 0.84448 \qquad (3.7.3)$$

$$C \quad 0.75 \times GH + 0.25 \qquad (3.7.4)$$

$$M = 0.0964284 - 0.096726 \times GH \qquad (3.7.5)$$

$$Le = h_c/(h_D\ c_{pa}) = C + M \times F(VMIN) \qquad (3.7.6)$$

The graphical representation of the same is available in [10].

3.8 Rate of Evaporation [10]

Here the mass of water evaporated in the process of cooling can be written as

$$\dot{m}_{ev} = \sum_{i=1}^{M} \dot{m}_{ai,N+1} (w_{i,N+1} - w_{i,1}) \qquad (3.8.1)$$

and in percentage $\dot{m}_{re} = (\dot{m}_{ev}/\dot{m}_w)\ 100$ (3.8.2)

3.9 Variable Cost Analysis [28]

1. Fan Power: The fan used should be of optimum size. It should handle the required volume of air against the resistance to flow. It is estimated on basis of pressure drop occurring during the process. The equation used is due to work of Kelly, N.W. and Swenson, L.K., where the total pressure drop is given by the sum of pressure drop due to fills and pressure drop due to falling water droplets, i.e.

$$\Delta P = [\, C1\ n\ \rho_a\ V_r^2 + 6C2\ n\ \rho_a\ V_r^2((\dot{m}_W/A\ (2\ Z_f/g)^{1/2})/(3600\ D_c\ \rho_W))\,] / 2g \qquad (3.9.1)$$

which is put in the following form

$$\Delta P = 25.4\, n \left[\rho_{av}/\rho_w \left(C3\, \dot{m}_a^2 + C4 \sqrt{Z_f}\, \dot{m}_w\, GE^2 \right) \right] \qquad (3.9.2)$$

where

$$GE^2 = \dot{m}_a^2 + \frac{4}{3}\, \dot{m}_a\, 3600\, \rho_a \sqrt{2g\, Z_f} + g\, (3600\, \rho_a)^2\, Z_f \qquad (3.9.3)$$

The values of C3 and C4 is given in Table 3.1 for the different fill arrangement shown in Fig. 2.6.

$$\text{Fan power} = (\Delta P\, (g/g_c)\, \rho_W\ \text{VOLSEC})/1000 \qquad (3.9.4)$$

$$\text{Cost of power/year} = \text{POWFAN X HR X OF X COP (X)} \qquad (3.9.5)$$

Cost of power/KW-hr is given by equation:

$$\text{COP (X)} = 1.2930/(0.97986 + e^{-0.09338\, X}) \qquad (3.9.6)$$

$$\text{and X} = \text{current year} - 1983 \qquad (3.9.7)$$

where Eq. (3.9.6) is derived based on the cost variation of power for past 15 years. The value of further years are predicted using Powel's method of optimization with current year as reference.

2. Water Cost: Total water circulated/hr = Initial water + Evaporation losses + Blow down + leakage

From Eq. (3.8.1) we know mass of water evaporated per hour.

$$\therefore\ \text{TOTWAT} = (\dot{m}_w (\dot{m}_{re} + \text{BLD} + \text{LKG} + \text{OTH})\ \text{HR OF})/100 \qquad (3.9.8)$$

$$\text{CWAT} = \text{TOTWAT WATCOST} \qquad (3.9.9)$$

3. Wood Cost:

VOLF = Cross-section area of fill X length of fill ... (3.9.10)

TABLE 3.1

CONSTANTS C3 AND C4 FROM EXPERIMENTAL RESULTS

DECK	VERTICAL SPACING	PLAN SOLIDITY FACTOR	VERTICAL FREE FALL ZF	C3 $\times 10^8$	C4 $\times 10^{12}$
A	0.75	0.250	3.00	0.34	0.11
B	1.00	0.250	4.00	0.34	0.11
C	1.25	0.333	3.75	0.40	0.14
D	2.00	0.333	6.00	0.40	0.14
E	2.00	0.404	4.95	0.60	0.15
F	2.00	0.219	9.13	0.26	0.07
G	2.00	0.292	6.85	0.40	0.10
H	2.00	0.550	3.64	0.75	0.26
I	2.00	0.440	4.50	0.52	0.16

CWOOD NOFILL X VOLF X CFIL (3.9.11)

4. Cost of Pumping Water Here actual head of pumping is assumed to be height of tower plus a meter.

Thus HEAD = Actual head + frictional head due to pipe friction

$$= (HIG + a + f_r \frac{(HIG + a)\, V_{wat}^2}{2g\, d_{pip}} \qquad (3.9.12)$$

where a = 1 meter and

$$d_{pip} = [4\dot{m}_W/(\rho_W\, V_{wat}\, X)]^{1/2} \qquad (3.9.13)$$

$$\therefore \quad PPOW = HEAD\, \dot{m}_W\, g \qquad (3.9.14)$$

$$PUMCOS = PPOW\ HR\ OF\ COP\ (X) \qquad (3.9.15)$$

3.10 Present Worth Method [28]

The unit value of costs is not identical different periods due to inter-temporal effects. This gives rise to the problem of reducing the costs to a particular base year and to make them commensurate with each other. The removal of these drawbacks gave rise to net present value approaches which can be expressed as

$$C_o = \sum_{LIFE=0}^{LIFE} \frac{C_t}{(1 + r_{int})^{LIFE}} \qquad (3.10.1)$$

Equation (3.10.1) can be used for all the running expenditures.

CHAPTER - 4

RESULT AND DISCUSSION

4.1 Selection of Grid Size

The grid size in the present computation has been selected after comparing the results for different combinations as given in Table 4.1. In case of 20 X 20 grid combination the time taken is 78% where the same result is obtained. From comparison with other combinations it is evident that 15 X 15 is the most desirable combination. It has been used for all other computations in the present investigation. Figure 4.1 shows the same graphically.

4.2 Iterative Scheme of Analysis

A generalized computer program is envisaged with a view to incorporate various constraints such as approach, range, water load, air flow rate, air inlet temperature etc. covering all practical ranges. Outlet water temperature and state of air is studied at every grid point for a typical cooling tower. The whole result can be represented in a tabular form as shown in Table 4.2. It is interesting to note that the

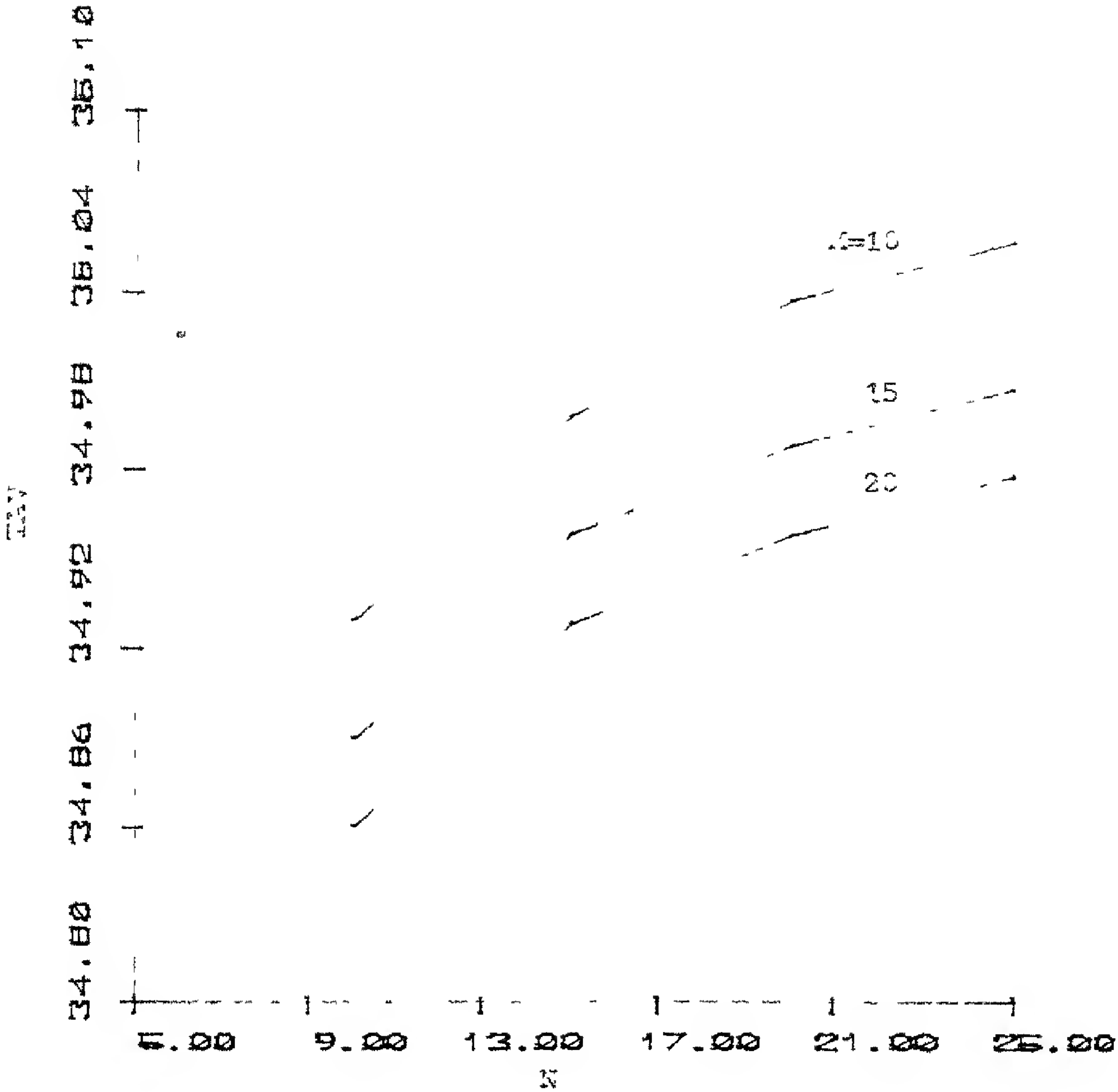


Fig 4.1 Grid selection

amount of heat transferred is very high for the grids near the top and it falls as we proceed towards basin as shown in Figs.4.2 to 4.4.

A desired outlet temperature of water was obtained using an iterative scheme for a given set of inlet conditions, size of tower by varying fills in order to change the surface area. The changes in fill is continued until the desired result is achieved. Table 4.3 gives the details of temperature profile through the tower developed after 5 iterative schemes.

We should have a free fall path for water droplet for heat transfer process. By increasing the number of fill material in a given size of tower means decreasing the free fall path. To incorporate this optimum free fall path iteration is terminated if it falls below minimum path. These are shown in Table 4.4 where iterations are carried out for different water flow rates.

In counter-flow this type of iterative analysis is not necessary. Here the desired output is obtained against the tower size. If we find that the tower is smaller for given conditions, the iteration is terminated and analysed for bigger size of tower and different flow rates.

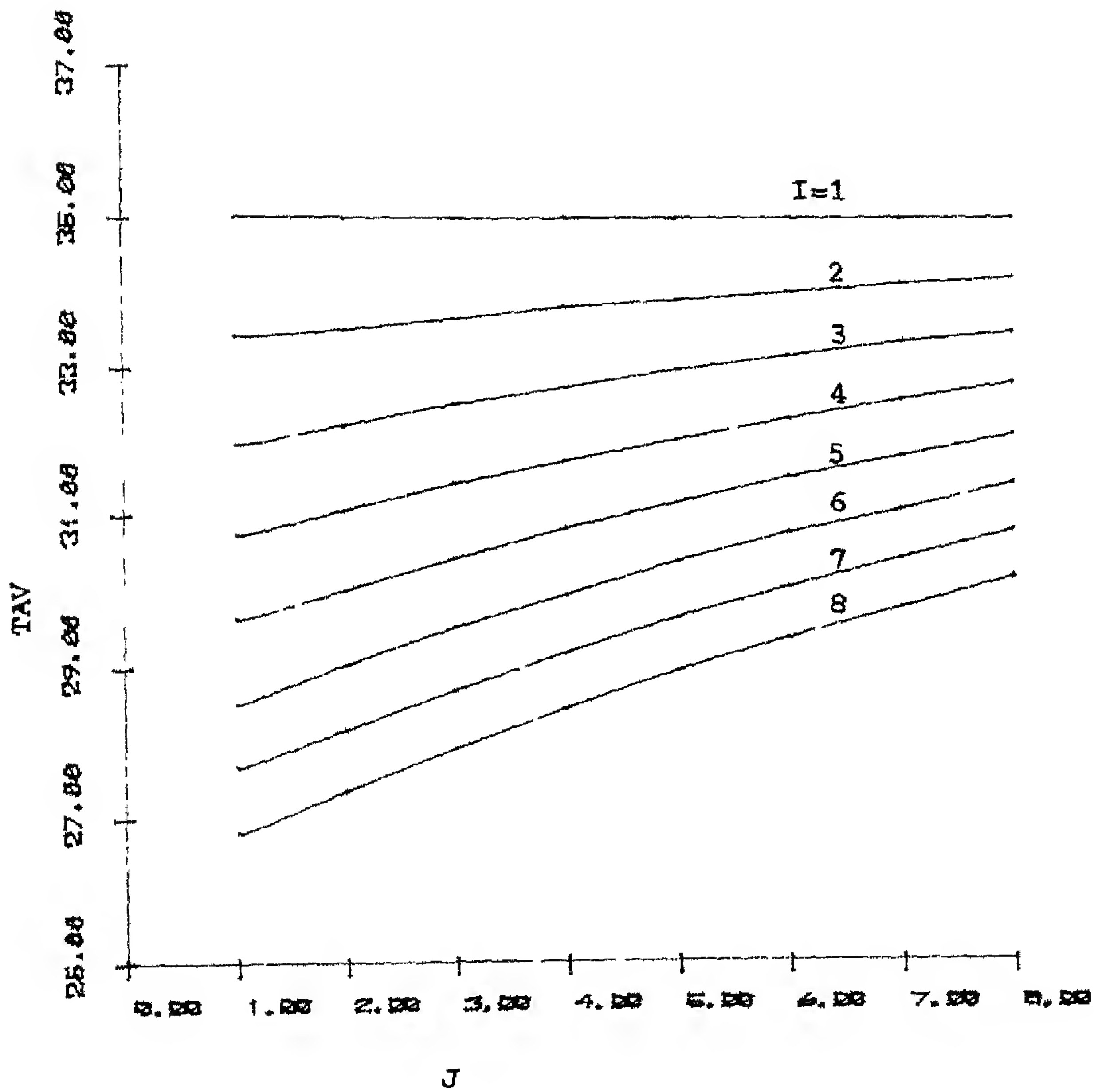


Fig 4.2 Variation of water temperature in each grid

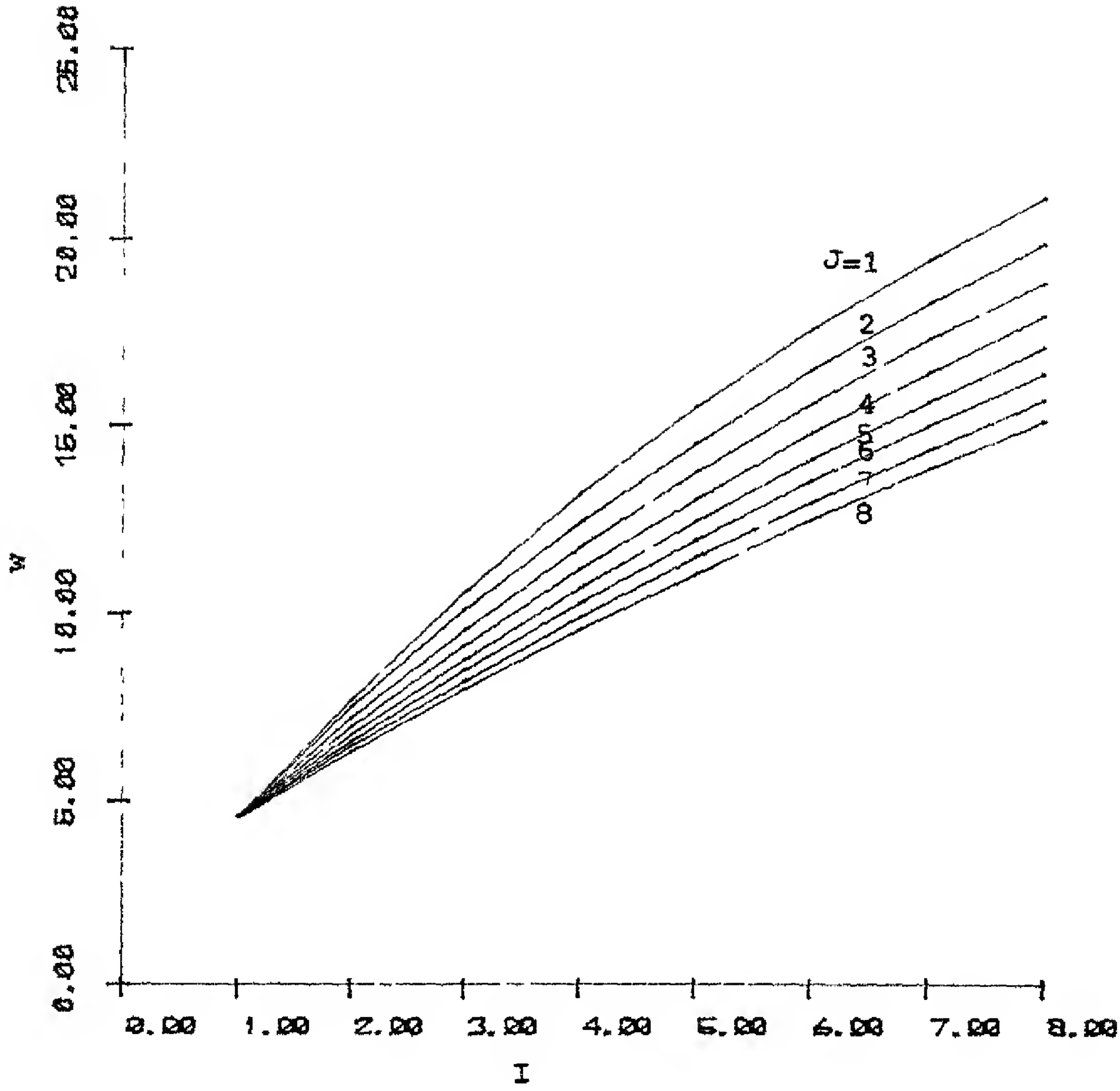


Fig 4.3 Variation of humidity of air in each grid

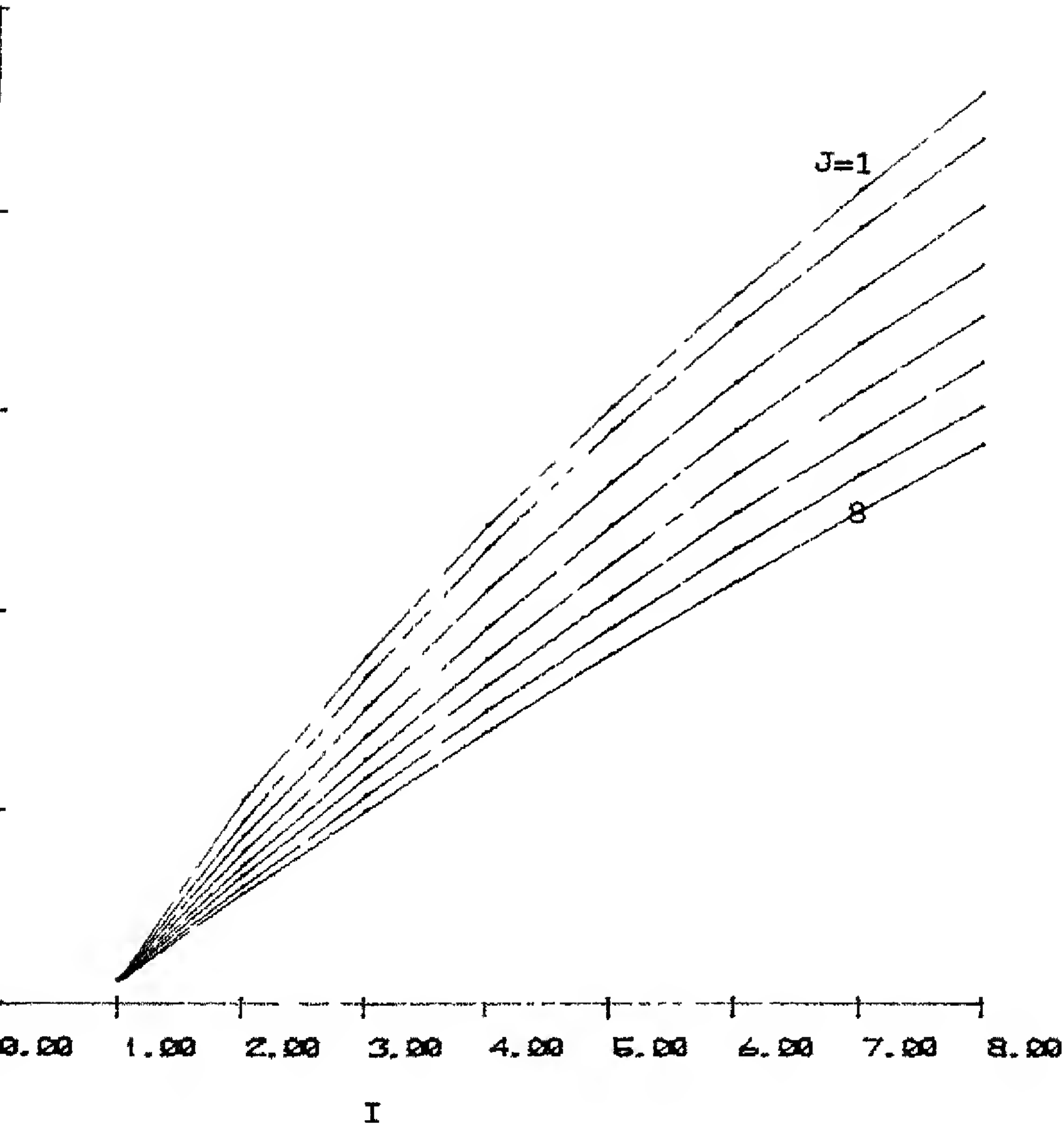


Fig 4.4 Variation of enthalpy of air in each grid

During this process the following results were noticed

1. To get a desired temperature higher by 2-5°C, than that for a given packing design, air flow rate has to be increased nearly 10 times the normal rate leading to larger fan size and its power.

2. If the difference between wet and dry bulb temperatures of air is less initially major part of heat transfer occurs due to evaporation and later the process is due to condensation.

4.3 Effect of Lewis Number

Lewis number is a function of inlet air velocity, dry and wet bulb temperature and inlet water temperature. Thus a change in Lewis number will have a direct effect on the final results. Its effect is studied for two sets of values and are presented in Table 4.5.a and 4.5.b. Change of about 2-4% in final result is found for a change in recommended Lewis number from 0.84 to 0.94. In order to get rid of this discrepancy variable Lewis number has been used as given by Eqs. (3.7.1 to 3.7.6

4.4 Tower Coefficients

The NTU serves as a measure in determining the tower performance. Tables (4.6.a to 4.6.d) reveals that NTU depends significantly on air flow rate as well as water

loading. Thus, NTU is a function of cooling factor as reported by [17].

The NTU method does not lend to complete mathematical solution. It is used as a verification method along with usual procedure of heat and mass transfer process. The cooling towers are specified in terms of $\dot{m}_W$, T1 , T2 , T3 , DEST.V. For a particular conditions the NTU and tower characteristic will be specified. This is known as required co-efficient. For various air flow rate we can determine the above co-efficients known as actual co-efficient as shown in Table (4.6.a to 4.6.d). Thus we can select a tower and flow rate such that the required size of tower.

Tables (4.6.a to 4.6.d) exhibits decrease in the tower coefficients with increase in range. Further the coefficients becomes negative at lower rate due to occurrence of condensation against evaporation. The details of calculating tower coefficients is shown in Table 4.7. In case of cross flow the variation in coefficients is shown in Table 4.8.

4.5 Volume, Heat Transfer and Evaporation in Tower Analysis

Tables 4-9 and 4-10 displays the comparison between the given volume of tower and estimated volume

4.6 Cost Anal sis

Fan power cost is calculated based on the pressure drop that is occurring in the tower. Fan power and pump power are combined together and estimated for various values of flow rates. Pump power is evaluated using the discharge rate and pumping head. The total cost for power is then found from Eqs. (3.9.6 and 3.9.15).

The cost variation for different flow rate are given in Table 4.11. It is found that the cost of water dominates among other costs. The fill cost is seen to be very less but even slight change in the fill influences the pumping cost considerably. All the values have been estimated based on the optimum number for given exit water condition.

4.7 Conclusions and Suggestions

A. Conclusions · From the present work the following conclusions can be derived:

1. The recommended grid size for the cross-flow cooling tower is 15 X 15 in view of saving of computational timing.
2. The effect of evaporation of water has to be considered while computing heat load capacity of the tower. Because it shows 6 to 8% higher values over the fixed mass results.

2. The effects of the recommended Lewis number are significant. Hence variable/average Lewis number suggested in the present paper be used.

3. The cost analysis shows that the make up water dominates over all other costs. This requires special care in the design aspect of a cooling tower. The present worth method has been used for the total cost.

4. For counter-flow tower the effects for evaporation of water on the exit temperature is also found to be in the same range as found for a cross-flow cooling tower.

B. Suggestions:

1. Better experimental data are required for heat and mass transfer coefficients for the solution of governing equations.

2. Further costs of various components of cooling tower should be collected from manufacturers for the exact cost analysis.

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TABLE 4.1 Average outlet water temperature v/s grid size

INLET CONDITIONS: T1=45 C
T2=28 C
T3=50 C

mw=30,000 kg/hr
V=2.5 m/sec

M \ N	5	10	15	20	25
10	34.72	34.93	35.00	35.04	35.06
15		34.89	34.96	34.99	35.01
20		34.86	34.93	34.95	34.99

...ix when variation of water temperature and state
****
of air
******

...ume of fill = 7.707 M**3
...ation info = 6 X 8

...Data :
...b temperature of air = 30.00 C
...b temperature of air = 15.00 C
...emperature on to the tower = 35.00 C
...water fed to the tower =50000.0kg/hr
...air blown =38976.1 kg/hr
...y of entering air = 41.28 kJ
...y of entering air =.004508 kg/kg of dry

35.000	35.000	35.000	35.000	35.000	35.000
7.153	10.672	13.297	15.658	17.781	19.691
47.015	55.955	63.421	70.125	76.145	81.557
33.523	33.672	33.814	33.935	34.043	34.141
7.574	10.157	12.558	14.744	16.735	18.548
49.513	56.729	63.274	69.236	74.665	79.609
32.254	32.518	32.757	32.973	33.168	33.344
7.234	9.652	11.877	13.923	15.805	17.535
48.538	55.139	61.132	66.655	71.745	76.433
31.037	31.453	31.775	32.009	32.335	32.578
6.995	9.229	11.390	13.221	15.002	16.654
47.981	53.791	59.391	64.430	69.204	73.646
30.212	30.471	30.852	31.219	31.545	31.843
6.725	9.809	10.896	12.614	14.303	15.880
47.235	52.647	57.719	62.491	66.974	71.182
29.076	29.563	30.003	30.419	30.795	31.139
6.625	8.560	10.378	12.086	13.690	15.197
46.587	51.642	55.339	60.789	65.002	68.989
28.187	28.722	29.213	29.606	30.082	30.466
6.478	8.292	10.005	11.622	13.148	14.589
46.208	50.769	55.174	59.282	63.246	67.025
27.368	27.942	28.458	28.955	29.406	29.823
6.351	8.058	9.677	11.211	12.666	14.046
45.789	49.999	54.049	57.940	61.675	65.257

...ity at each grid = W*1000

...ing :
...temperature of leaving water = 27.96 C
...enthalpy of leaving air = 80.81 kJ
...y of leaving air =.019418 kg/kg of dry

...water evaporated = 581.1 kg/hr
...leased = 1540869.4 kJ/hr
...of fill required = 292
...of tower operation
...oration rate = 6.8250 M**3

4. Details of Water Temperature at Ev[illegible]
****

[illegible] T = .1598+02 [illegible] = .350E+02

[illegible] = 0.4508E-02

[illegible] of Water Temperature at Every Grid Point

[illegible]	35.000	35.000	35.000	35.000	35.000	35.000
[illegible]	33.808	33.967	34.057	34.140	34.215	34.284
[illegible]	32.823	33.095	33.171	33.323	33.403	33.501
[illegible]	31.657	32.108	32.336	32.547	32.742	32.921
[illegible]	31.039	31.250	31.549	31.811	32.052	32.276
[illegible]	30.124	30.478	30.806	31.110	31.392	31.654
[illegible]	29.344	29.736	30.104	30.445	30.761	31.055
[illegible]	28.615	29.042	29.440	29.811	30.157	30.490
[illegible]	27.931	28.386	28.811	29.208	29.579	29.927

[illegible] of Water Temperature at Every Grid Point

[illegible]	35.000	35.000	35.000	35.000	35.000	35.000
[illegible]	33.652	33.793	33.920	34.033	34.134	34.225
[illegible]	32.469	32.719	32.944	33.147	33.330	33.494
[illegible]	31.385	31.721	32.027	32.307	32.555	32.783
[illegible]	30.347	30.794	31.165	31.504	31.812	32.093
[illegible]	29.365	29.830	30.355	30.744	31.100	31.427
28.057	28.613	29.123	29.592	30.023	30.420	30.794
27.278	27.822	28.359	28.873	29.339	29.769	30.160
[illegible]	27.086	27.652	28.196	28.690	29.147	29.572

[illegible] of Water Temperature at Every Grid Point

35.000	35.000	35.000	35.000	35.000	35.000	35.000
33.501	33.657	33.797	33.922	34.034	34.135	34.225
32.290	32.480	32.727	32.959	33.151	33.332	33.495
31.233	31.409	31.734	32.036	32.311	32.560	32.786
29.954	30.407	30.810	31.179	31.513	31.819	32.098
[illegible]	29.489	29.919	30.370	30.755	31.109	31.433
28.089	28.639	29.145	29.610	30.037	30.431	30.793
27.262	27.851	28.373	28.893	29.355	29.782	30.176
[illegible]	27.117	27.688	28.217	28.708	29.162	29.583

[illegible] of Water Temperature at Every Grid Point

35.000	35.000	35.000	35.000	35.000	35.000	35.000
33.510	33.601	33.802	33.926	34.037	34.137	34.226
32.292	32.493	32.727	32.957	33.155	33.336	33.496
31.054	31.418	31.748	32.047	32.319	32.566	32.790
29.990	30.428	30.827	31.191	31.523	31.827	32.104
29.016	29.514	29.959	30.385	30.769	31.119	31.441
28.122	28.667	29.167	29.628	30.052	30.442	30.802
27.297	27.880	28.418	28.914	29.372	29.795	30.187
26.536	27.148	27.715	28.240	28.726	29.177	29.596

[illegible] of Water Temperature at Every Grid Point

[illegible]	35.000	35.000	35.000	35.000	35.000	35.000
[illegible]	[illegible]	33.804	33.930	34.040	34.139	34.227
[illegible]	[illegible]	32.737	32.965	33.162	33.340	33.501
[illegible]	31.435	[illegible]	32.058	32.327	32.572	32.794
[illegible]	30.440	[illegible]	31.205	31.534	31.835	32.109
[illegible]	29.538	29.989	30.402	30.781	31.129	31.448
[illegible]	28.691	[illegible]	29.647	30.057	30.454	30.811
[illegible]	27.910	28.435	28.935	29.389	29.809	30.198
[illegible]	[illegible]	[illegible]	28.262	28.745	29.193	29.608

[illegible] = 0.6925E+01

[illegible] = 0.7334E+01

[illegible] = 0.5911E+03

[illegible] = 0.1102E+01

[illegible] = 0.1537255E+07

[illegible] 0.4429E+02

[illegible] 0.7834E+02

[illegible] 4029.7270

Detail of iterations in attaining desired
****

[illegible]	T1	T2	T3	DESTAV	V	EMA
7	30.0	15.0	35.0	20.0	2.0	30000.
8	30.0	15.0	35.0	20.0	2.0	30000.
[illegible]	30.0	15.0	35.0	20.0	2.0	30000.
1	30.0	15.0	35.0	20.0	2.0	30000.
[illegible]	30.0	15.0	35.0	20.0	2.0	30000.
[illegible]	30.0	15.0	35.0	20.0	2.0	30000.
5	30.0	15.0	35.0	20.0	2.0	30000.
[illegible]	30.0	15.0	35.0	20.0	2.0	30000.
7	30.0	15.0	35.0	20.0	2.0	30000.

OPEN FILE > TWICE THE SIZE OF THE FILE

7	30.0	15.0	35.0	28.0	2.0	50000.
7	30.0	15.0	35.0	28.0	2.0	50000.
7	30.0	15.0	35.0	28.0	2.0	50000.
7	30.0	15.0	35.0	28.0	2.0	50000.
7	30.0	15.0	35.0	28.0	2.0	50000.

7	30.0	15.0	35.0	29.0	2.0	70000.
8	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.
[illegible]	30.0	15.0	35.0	29.0	2.0	70000.

1.5.? Effect of [illegible] number v/s exit water t
****

[illegible]	T3	[illegible]	[illegible]	[illegible]	[illegible]	TAV
1.0	33.0	.84	30000.0	48720.1	87.50	27.15
1.0	33.0	.84	50000.0	48720.1	90.51	28.83
1.0	33.0	.84	70000.0	48720.1	92.08	29.77
1.0	36.0	.84	30000.0	48720.1	93.17	28.04
1.0	36.0	.84	50000.0	48720.1	97.62	30.25
1.0	36.0	.84	70000.0	48720.1	100.01	31.52
2.0	33.0	.84	30000.0	48720.1	82.61	26.07
2.0	33.0	.84	50000.0	48720.1	85.08	28.08
2.0	33.0	.84	70000.0	48720.1	87.90	29.20
2.0	36.0	.84	30000.0	48720.1	88.21	26.99
2.0	36.0	.84	50000.0	48720.1	93.17	29.51
2.0	36.0	.84	70000.0	48720.1	95.76	30.95
9.0	38.0	.84	30000.0	47927.1	112.25	31.45
9.0	38.0	.84	50000.0	47927.1	116.42	33.17
9.0	38.0	.84	70000.0	47927.1	118.09	34.20
9.0	41.0	.84	30000.0	47927.1	118.07	32.14
9.0	41.0	.84	50000.0	47927.1	124.76	34.36
9.0	41.0	.84	70000.0	47927.1	128.18	35.73
7.0	38.0	.84	30000.0	47927.1	105.93	30.23
7.0	38.0	.84	50000.0	47927.1	110.77	32.30
7.0	38.0	.84	70000.0	47927.1	113.31	33.53
7.0	41.0	.84	30000.0	47927.1	112.25	30.93
7.0	41.0	.84	50000.0	47927.1	118.96	33.51
7.0	41.0	.84	70000.0	47927.1	122.73	35.08
[illegible].0	43.0	.84	30000.0	47157.6	142.73	35.77
[illegible].0	43.0	.84	50000.0	47157.6	148.44	37.45
[illegible].0	43.0	.84	70000.0	47157.6	151.68	38.55
[illegible].0	46.0	.84	30000.0	47157.6	149.87	36.23
[illegible].0	46.0	.84	50000.0	47157.6	158.10	38.40
[illegible].0	46.0	.84	70000.0	47157.6	162.92	39.85
[illegible].0	43.0	.84	30000.0	47157.6	131.45	34.39
[illegible].0	43.0	.84	50000.0	47157.6	141.00	36.45
[illegible].0	43.0	.84	70000.0	47157.6	144.77	37.76
[illegible].0	46.0	.84	30000.0	47157.6	141.50	34.89
[illegible].0	46.0	.84	50000.0	47157.6	150.53	37.42
[illegible].0	46.0	.84	70000.0	47157.6	155.83	39.08
[illegible].0	48.0	.84	30000.0	46411.6	180.55	40.14
[illegible].0	48.0	.84	50000.0	46411.6	188.20	41.70
[illegible].0	48.0	.84	70000.0	46411.6	192.78	42.82
[illegible].0	51.0	.84	30000.0	46411.6	188.36	40.43
[illegible].0	51.0	.84	50000.0	46411.6	199.22	42.41
[illegible].0	51.0	.84	70000.0	46411.6	205.96	43.87
[illegible].0	48.0	.84	30000.0	46411.6	169.69	38.61
[illegible].0	48.0	.84	50000.0	46411.6	174.36	40.55
[illegible].0	48.0	.84	70000.0	46411.6	183.61	41.91
[illegible].0	51.0	.84	30000.0	46411.6	177.31	38.93
[illegible].0	51.0	.84	50000.0	46411.6	189.24	41.29
[illegible].0	51.0	.84	70000.0	46411.6	196.62	42.98

TABLE 4.5.8 Effect of Lewis number v/s exit water
****

TW	MS	XWT	PMW	T1A	HAV	TAV
TW	MS	XWT	PMW	T1A	HAV	TAV
24.0	33.0	.91	30000.0	48720.1	86.76	27.4
24.0	33.0	.91	50000.0	48720.1	89.50	29.0
24.0	33.0	.91	70000.0	48720.1	90.92	29.9
24.0	36.0	.91	30000.0	48720.1	92.26	28.3
24.0	36.0	.91	50000.0	48720.1	90.32	30.5
24.0	36.0	.91	70000.0	48720.1	98.18	31.7
22.0	33.0	.91	30000.0	48720.1	81.71	26.4
22.0	33.0	.91	50000.0	48720.1	84.87	28.3
22.0	33.0	.91	70000.0	48720.1	86.51	29.1
22.0	36.0	.91	30000.0	48720.1	87.14	27.3
22.0	36.0	.91	50000.0	48720.1	91.62	29.8
22.0	36.0	.91	70000.0	48720.1	94.01	31.2
29.0	38.0	.91	30000.0	47927.1	111.49	31.7
29.0	38.0	.91	50000.0	47927.1	115.29	33.4
29.0	38.0	.91	70000.0	47927.1	117.34	34.4
29.0	41.0	.91	30000.0	47927.1	117.72	32.4
29.0	41.0	.91	50000.0	47927.1	123.31	34.6
29.0	41.0	.91	70000.0	47927.1	126.41	36.0
27.0	38.0	.91	30000.0	47927.1	104.90	30.5
27.0	38.0	.91	50000.0	47927.1	109.36	32.6
27.0	38.0	.91	70000.0	47927.1	111.73	33.7
27.0	41.0	.91	30000.0	47927.1	111.14	31.3
27.0	41.0	.91	50000.0	47927.1	117.29	33.8
27.0	41.0	.91	70000.0	47927.1	120.70	35.35
34.0	43.0	.91	30000.0	47157.6	141.90	36.04
34.0	43.0	.91	50000.0	47157.6	147.21	37.71
34.0	43.0	.91	70000.0	47157.6	150.15	38.70
34.0	46.0	.91	30000.0	47157.6	148.95	36.56
34.0	46.0	.91	50000.0	47157.6	156.53	38.73
34.0	46.0	.91	70000.0	47157.6	160.92	40.15
32.0	43.0	.91	30000.0	47157.6	133.52	34.73
32.0	43.0	.91	50000.0	47157.6	139.51	36.77
32.0	43.0	.91	70000.0	47157.6	142.87	38.04
32.0	46.0	.91	30000.0	47157.6	140.10	35.28
32.0	46.0	.91	50000.0	47157.6	148.71	37.81
32.0	46.0	.91	70000.0	47157.6	153.54	39.43
39.0	48.0	.91	30000.0	46411.6	179.67	40.36
39.0	48.0	.91	50000.0	46411.6	186.91	41.97
39.0	48.0	.91	70000.0	46411.6	191.08	43.08
39.0	51.0	.91	30000.0	46411.6	187.53	40.72
39.0	51.0	.91	50000.0	46411.6	197.60	42.75
39.0	51.0	.91	70000.0	46411.6	203.76	44.20
37.0	48.0	.91	30000.0	46411.6	168.72	38.92
37.0	48.0	.91	50000.0	46411.6	176.79	40.87
37.0	48.0	.91	70000.0	46411.6	181.57	42.21
37.0	51.0	.91	30000.0	46411.6	176.29	39.78
37.0	51.0	.91	50000.0	46411.6	187.34	41.68
37.0	51.0	.91	70000.0	46411.6	191.09	43.30

[illegible] coefficients in case of counter
****

TI	DELTW	DT	PIN	MA/MV	NTU
25.	16.0	.500	30000.0	.80	0.578
25.	16.0	.500	30000.0	1.00	0.409
25.	16.0	.500	30000.0	1.20	0.352
25.	16.0	.500	30000.0	1.40	0.322
25.	16.0	.500	30000.0	1.60	0.304
25.	16.0	.500	30000.0	1.80	0.291
30.	21.0	.500	30000.0	.80	0.354
30.	21.0	.500	30000.0	1.00	0.288
30.	21.0	.500	30000.0	1.20	0.261
30.	21.0	.500	30000.0	1.40	0.245
30.	21.0	.500	30000.0	1.60	0.234
30.	21.0	.500	30000.0	1.80	0.227
35.	26.0	.500	30000.0	.80	0.242
35.	26.0	.500	30000.0	1.00	0.210
35.	26.0	.500	30000.0	1.20	0.196
35.	26.0	.500	30000.0	1.40	0.187
35.	26.0	.500	30000.0	1.60	0.181
35.	26.0	.500	30000.0	1.80	0.177
40.	31.0	.500	30000.0	.80	0.173
40.	31.0	.500	30000.0	1.00	0.156
40.	31.0	.500	30000.0	1.20	0.148
40.	31.0	.500	30000.0	1.40	0.143
40.	31.0	.500	30000.0	1.60	0.140
40.	31.0	.500	30000.0	1.80	0.137
45.	36.0	.500	30000.0	.80	0.127
45.	36.0	.500	30000.0	1.00	0.117
45.	36.0	.500	30000.0	1.20	0.113
45.	36.0	.500	30000.0	1.40	0.110
45.	36.0	.500	30000.0	1.60	0.108
45.	36.0	.500	30000.0	1.80	0.106
50.	41.0	.500	30000.0	.80	0.095
50.	41.0	.500	30000.0	1.00	0.088
50.	41.0	.500	30000.0	1.20	0.086
50.	41.0	.500	30000.0	1.40	0.084
50.	41.0	.500	30000.0	1.60	0.083
50.	41.0	.500	30000.0	1.80	0.082

Table 4.6.6 Power coefficients in case of counter fl

T1	T2	T3	DESIGN	UT	FIN	MA/MW	NTU	TJ
20.	5.	25.	16.0	.600	70000.0	.80	0.578	3.
20.	5.	25.	16.0	.600	70000.0	1.00	0.409	1.
20.	5.	25.	16.0	.600	70000.0	1.20	0.352	1.
20.	5.	25.	16.0	.600	70000.0	1.40	0.322	0.
20.	5.	25.	16.0	.600	70000.0	1.60	0.304	0.
20.	5.	25.	16.0	.600	70000.0	1.80	0.291	0.
25.	10.	30.	21.0	.600	70000.0	.80	0.354	1.
25.	10.	30.	21.0	.600	70000.0	1.00	0.288	1.
25.	10.	30.	21.0	.600	70000.0	1.20	0.261	0.
25.	10.	30.	21.0	.600	70000.0	1.40	0.245	0.
25.	10.	30.	21.0	.600	70000.0	1.60	0.234	0.
25.	10.	30.	21.0	.600	70000.0	1.80	0.227	0.
30.	15.	35.	26.0	.600	70000.0	.80	0.242	1.
30.	15.	35.	26.0	.600	70000.0	1.00	0.210	0.
30.	15.	35.	26.0	.600	70000.0	1.20	0.196	0.
30.	15.	35.	26.0	.600	70000.0	1.40	0.187	0.
30.	15.	35.	26.0	.600	70000.0	1.60	0.181	0.
30.	15.	35.	26.0	.600	70000.0	1.80	0.177	0.
35.	20.	40.	31.0	.600	70000.0	.80	0.173	0.[illegible]
35.	20.	40.	31.0	.600	70000.0	1.00	0.156	0.[illegible]
35.	20.	40.	31.0	.600	70000.0	1.20	0.148	0.[illegible]
35.	20.	40.	31.0	.600	70000.0	1.40	0.143	0.[illegible]
35.	20.	40.	31.0	.600	70000.0	1.60	0.140	0.[illegible]
35.	20.	40.	31.0	.600	70000.0	1.80	0.137	0.[illegible]
40.	25.	45.	36.0	.600	70000.0	.80	0.127	0.[illegible]
40.	25.	45.	36.0	.600	70000.0	1.00	0.117	0.5
40.	25.	45.	36.0	.600	70000.0	1.20	0.113	0.4
40.	25.	45.	36.0	.600	70000.0	1.40	0.110	0.3
40.	25.	45.	36.0	.600	70000.0	1.60	0.108	0.3
40.	25.	45.	36.0	.600	70000.0	1.80	0.106	0.2
45.	30.	50.	41.0	.600	70000.0	.80	0.095	0.5
45.	30.	50.	41.0	.600	70000.0	1.00	0.088	0.3
45.	30.	50.	41.0	.600	70000.0	1.20	0.086	0.3
45.	30.	50.	41.0	.600	70000.0	1.40	0.084	0.2
45.	30.	50.	41.0	.600	70000.0	1.60	0.083	0.2
45.	30.	50.	41.0	.600	70000.0	1.80	0.082	0.2

[illegible] joint coefficients in case of counter flow tower
****

T_1	T_2	T_3	[illegible]	DT	[illegible]	VA/VW	[illegible]	[illegible]
20.	5.	25.	10.0	1.000	30000.0	.80	-2.454	-13.135
20.	5.	25.	10.0	1.000	30000.0	1.00	-1.242	-5.465
20.	5.	25.	10.0	1.000	30000.0	1.20	3.200	11.452
20.	5.	25.	10.0	1.000	30000.0	1.40	1.616	4.967
20.	5.	25.	10.0	1.000	30000.0	1.60	1.240	3.338
20.	5.	25.	10.0	1.000	30000.0	1.80	1.003	2.546
25.	10.	30.	15.0	1.000	30000.0	.80	-2.555	-41.424
25.	10.	30.	15.0	1.000	30000.0	1.00	2.541	10.997
25.	10.	30.	15.0	1.000	30000.0	1.20	1.242	4.190
25.	10.	30.	15.0	1.000	30000.0	1.40	0.955	2.963
25.	10.	30.	15.0	1.000	30000.0	1.60	0.823	2.236
25.	10.	30.	15.0	1.000	30000.0	1.80	0.746	1.803
30.	15.	35.	20.0	1.000	30000.0	.80	2.576	14.022
30.	15.	35.	20.0	1.000	30000.0	1.00	0.982	4.295
30.	15.	35.	20.0	1.000	30000.0	1.20	0.740	2.701
30.	15.	35.	20.0	1.000	30000.0	1.40	0.637	1.992
30.	15.	35.	20.0	1.000	30000.0	1.60	0.578	1.584
30.	15.	35.	20.0	1.000	30000.0	1.80	0.541	1.317
35.	20.	40.	25.0	1.000	30000.0	.80	0.842	4.628
35.	20.	40.	25.0	1.000	30000.0	1.00	0.581	2.566
35.	20.	40.	25.0	1.000	30000.0	1.20	0.494	1.818
35.	20.	40.	25.0	1.000	30000.0	1.40	0.448	1.414
35.	20.	40.	25.0	1.000	30000.0	1.60	0.419	1.157
35.	20.	40.	25.0	1.000	30000.0	1.80	0.400	0.981
40.	25.	45.	30.0	1.000	30000.0	.80	0.487	2.703
40.	25.	45.	30.0	1.000	30000.0	1.00	0.386	1.717
40.	25.	45.	30.0	1.000	30000.0	1.20	0.347	1.287
40.	25.	45.	30.0	1.000	30000.0	1.40	0.324	1.031
40.	25.	45.	30.0	1.000	30000.0	1.60	0.309	0.861
40.	25.	45.	30.0	1.000	30000.0	1.80	0.299	0.739
45.	30.	50.	35.0	1.000	30000.0	.80	0.320	1.794
45.	30.	50.	35.0	1.000	30000.0	1.00	0.270	1.210
45.	30.	50.	35.0	1.000	30000.0	1.20	0.251	0.937
45.	30.	50.	35.0	1.000	30000.0	1.40	0.239	0.765
45.	30.	50.	35.0	1.000	30000.0	1.60	0.231	0.647
45.	30.	50.	35.0	1.000	30000.0	1.80	0.225	0.560

TABLE 4.6.6 Lower coefficients in case of count
****

T2	T3	DESTAV	DT	TMW	MA/MN	NTU
5.	25.	10.0	1.000	70000.0	.80	-2.454
5.	25.	10.0	1.000	70000.0	1.00	-1.292
5.	25.	10.0	1.000	70000.0	1.20	3.200
5.	25.	10.0	1.000	70000.0	1.40	1.616
5.	25.	10.0	1.000	70000.0	1.60	1.240
5.	25.	10.0	1.000	70000.0	1.80	1.063
10.	30.	15.0	1.000	70000.0	.80	-2.555
10.	30.	15.0	1.000	70000.0	1.00	2.541
10.	30.	15.0	1.000	70000.0	1.20	1.742
10.	30.	15.0	1.000	70000.0	1.40	0.955
10.	30.	15.0	1.000	70000.0	1.60	0.823
10.	30.	15.0	1.000	70000.0	1.80	0.746
15.	35.	20.0	1.000	70000.0	.80	2.576
15.	35.	20.0	1.000	70000.0	1.00	0.982
15.	35.	20.0	1.000	70000.0	1.20	0.740
15.	35.	20.0	1.000	70000.0	1.40	0.637
15.	35.	20.0	1.000	70000.0	1.60	0.578
15.	35.	20.0	1.000	70000.0	1.80	0.541
20.	40.	25.0	1.000	70000.0	.80	0.842
20.	40.	25.0	1.000	70000.0	1.00	0.581
20.	40.	25.0	1.000	70000.0	1.20	0.494
20.	40.	25.0	1.000	70000.0	1.40	0.448
20.	40.	25.0	1.000	70000.0	1.60	0.419
20.	40.	25.0	1.000	70000.0	1.80	0.400
25.	45.	30.0	1.000	70000.0	.80	0.487
25.	45.	30.0	1.000	70000.0	1.00	0.386
25.	45.	30.0	1.000	70000.0	1.20	0.347
25.	45.	30.0	1.000	70000.0	1.40	0.324
25.	45.	30.0	1.000	70000.0	1.60	0.309
25.	45.	30.0	1.000	70000.0	1.80	0.299
30.	50.	35.0	1.000	70000.0	.80	0.320
30.	50.	35.0	1.000	70000.0	1.00	0.270
30.	50.	35.0	1.000	70000.0	1.20	0.251
30.	50.	35.0	1.000	70000.0	1.40	0.239
30.	50.	35.0	1.000	70000.0	1.60	0.231
30.	50.	35.0	1.000	70000.0	1.80	0.225

coefficient calculation details
****

T1	T2	T3	DISLAV	DI	VELOCITY	TMW
[illegible]	[illegible]	35 00000	26 00000	0 6000000	2 500000	30000 00

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	LN DIFF (IS=M)	FRAC EN DIFF	MEAN OF FRAC	NTU	SUM NTU	IDCH
[illegible]	[illegible]	[illegible]	[illegible]	41 279	33 185	0 02552	02573	0 0154	0 0154	0 0846
[illegible]	[illegible]	[illegible]	[illegible]	41 565	38 [illegible]	0 02593	0 02612	0 0157	0 0311	0 0859
[illegible]	[illegible]	[illegible]	[illegible]	17 [illegible]	38 013	0 02631	0 02647	0 0159	0 0470	0 0871
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	37 [illegible]	0 02664	0 02678	0 0161	0 0631	0 0881
[illegible]	[illegible]	[illegible]	[illegible]	54 131	37 137	0 02693	0 02705	0 0162	0 0793	0 0890
[illegible]	[illegible]	[illegible]	[illegible]	57 721	36 [illegible]	0 02716	0 02725	0 0164	0 0956	0 0897
[illegible]	[illegible]	[illegible]	[illegible]	61 011	36 571	0 02734	0 02740	0 0164	0 1121	0 0902
[illegible]	[illegible]	[illegible]	[illegible]	64 [illegible]	36 [illegible]	0.02746	0 02749	0 0165	0 1286	0 0905
[illegible]	[illegible]	[illegible]	103 [illegible]	67 [illegible]	36 [illegible]	0 02752	0 02751	0 0165	0 1451	0 0906
[illegible]	[illegible]	[illegible]	[illegible]	70 885	36 351	0 02751	0 02747	0 0165	0 1616	0 0905
[illegible]	[illegible]	[illegible]	[illegible]	74 177	36 157	0 02743	0 02736	0 0164	0 1780	0.0901
[illegible]	[illegible]	[illegible]	[illegible]	77 471	36 [illegible]	0 02728	0 02717	0 0163	0 1943	0 0895
[illegible]	[illegible]	[illegible]	[illegible]	80 766	36 953	0 02706	0 02692	0 0162	0.2104	0 0887
[illegible]	[illegible]	[illegible]	[illegible]	84 [illegible]	37 350	0 02677	0.02660	0 0160	0 2264	0.0877
[illegible]	[illegible]	[illegible]	125 209	87 350	37 850	0 02642	0 02621	0 0157	0 2421	0 0865
[illegible]	[illegible]	[illegible]	[illegible]	90 659	33 850	0 02600				

T1	T2	T3	DISLAV	DI	VELOCITY	TMW
35 [illegible]	30 0 00	50 00000	41 00000	0.6000000	2 500000	30000.00

[illegible]	[illegible]	[illegible]	[illegible]	ATM [illegible]	LN DIFF (IS=I)	FRAC EN DIFF	MEAN OF FRAC	NTU	SUM NTU	IDCH
[illegible]	[illegible]	[illegible]	[illegible]	99 839	76 137	0 01313	0.01297	0.0078	0.0078	0.0436
[illegible]	[illegible]	[illegible]	[illegible]	102 197	78 140	0 01280	0 01263	0 0076	0 0154	0.0424
[illegible]	[illegible]	[illegible]	[illegible]	105 558	80 304	0 01245	0 01228	0 0074	0.0227	0.0413
[illegible]	[illegible]	[illegible]	[illegible]	108 920	82 633	0 01210	0 01192	0 0072	0 0299	0 0401
0 107	[illegible]	[illegible]	[illegible]	112 [illegible]	85 133	0 01175	0 01157	0 0069	0 0368	0 0389
[illegible]	[illegible]	[illegible]	[illegible]	115 648	87 [illegible]	0 01139	0 01121	0.0067	0.0435	0.0377

0.2[illegible]	[illegible]	15.[illegible]	222.1[illegible]	125.751	95.57[illegible]	0.01031	0.01013	0.0061	0.0624	0.0342
[illegible]	[illegible]	[illegible]	229.519	129.127	100.427	0.00996	0.00978	0.0059	0.0683	0.0330
0.30[illegible]	[illegible]	17.[illegible]	236.397	132.135	104.071	0.00961	0.00943	0.0057	0.0740	0.0319
0.[illegible]	6.60[illegible]	17.5[illegible]	243.340	135.970	107.975	0.00926	0.00909	0.0055	0.0794	0.0307
[illegible]	7.[illegible]	[illegible]	251.335	137.219	112.087	0.00892	0.00876	0.0053	0.0847	0.0296
0.[illegible]	7.[illegible]	[illegible]	259.062	142.627	116.435	0.00859	0.00843	0.0051	0.0897	0.0285
0.5[illegible]	[illegible]	[illegible]	267.037	145.909	121.028	0.00826	0.00810	0.0049	0.0946	0.0274
0.5[illegible]	[illegible]	[illegible]	275.269	149.394	125.875	0.00794				

TABLE 4.8 Detail of variation of tower coefficient in every grid point

VOLUME OF TOWER USED = 7.767 M**3
NUMBER OF GRIDS USED = 8 X 8

INPUT CONDITIONS :

Dry bulb temperature of Air	= 30.00 C
Wet bulb temperature of air	= 15.00 C
Water temperature on to the Tower	= 35.00 C
Mass of water fed to the tower	=50000.0kg/hr
Mass of air blown	=38976.1 Kg/hr
enthalpy of entering air	= 41.28 KJ
Humidity of entring air	=.004508 Kg/kg of dry air

SUMNTU = 0.016 SUMTPCH= 0.107	0.036 0.210	0.055 0.312	0.074 0.415	0.093 0.517	0.112 0.620	0.131 0.722	0.150 0.825
SUMNTU = 0.019 SUMTPCH= 0.103	0.038 0.205	0.057 0.308	0.076 0.411	0.095 0.513	0.114 0.616	0.132 0.718	0.151 0.820
SUMNTU = 0.019 SUMTPCH= 0.103	0.038 0.205	0.057 0.308	0.076 0.411	0.095 0.513	0.114 0.616	0.132 0.719	0.151 0.821
SUMNTU = 0.019 SUMTPCH= 0.103	0.038 0.206	0.058 0.309	0.076 0.411	0.095 0.513	0.114 0.616	0.133 0.718	0.151 0.821
SUMNTU = 0.019 SUMTPCH= 0.103	0.039 0.206	0.058 0.309	0.077 0.411	0.095 0.514	0.114 0.616	0.133 0.719	0.152 0.821
SUMNTU = 0.019 SUMTPCH= 0.103	0.039 0.206	0.058 0.309	0.077 0.412	0.096 0.514	0.114 0.617	0.133 0.719	0.152 0.822
SUMNTU = 0.019 SUMTPCH= 0.103	0.039 0.206	0.058 0.309	0.077 0.412	0.096 0.515	0.115 0.618	0.133 0.720	0.152 0.823
SUMNTU = 0.009 SUMTPCH= 0.026	0.019 0.052	0.028 0.077	0.037 0.103	0.046 0.129	0.055 0.154	0.065 0.180	0.074 0.206

OUTPUT CONDITIONS :

Average temperature of leaving water	= 27.96 C
Average enthalpy of leaving air	= 80.81 KJ
Humidity of leaving air	=.019418 Kg/kg of dry air

RESULTS :

Mass of water evaporated	= 581.1 Kg/hr
Heat released	= 1540869.4 KJ/hr
Number of fill required	= 292
Volume of tower based on evaporation rate	= 6.8250 M**3

TABLE 4.9 Comparision of volume of tower based on tower dimensions and humidity

T1	T2	T3	TAW	V	TAV	VOLUME BASED ON DIM	HUMID
[illegible]	15.0	35.0	30000.0	2.5	19.99	7.787	6.844
[illegible]	15.0	35.0	50000.0	1.5	27.35	7.787	6.840
[illegible]	15.0	35.0	50000.0	2.0	27.95	7.787	6.825
[illegible]	15.0	35.0	50000.0	2.5	27.97	7.787	6.820
[illegible]	15.0	35.0	70000.0	1.5	28.94	7.787	6.863
[illegible]	15.0	35.0	70000.0	2.0	28.95	7.787	6.832
[illegible]	15.0	35.0	70000.0	2.5	28.94	7.787	6.824
[illegible]	25.0	45.0	30000.0	2.0	29.95	7.787	6.835
[illegible]	25.0	45.0	30000.0	2.5	29.95	7.787	6.829
[illegible]	25.0	45.0	50000.0	1.5	37.97	7.787	6.822
[illegible]	25.0	45.0	50000.0	2.0	37.99	7.787	6.818
[illegible]	25.0	45.0	50000.0	2.5	37.94	7.787	6.816
[illegible]	25.0	45.0	70000.0	1.5	38.95	7.787	6.826
[illegible]	25.0	45.0	70000.0	2.0	38.97	7.787	6.820
[illegible]	25.0	45.0	70000.0	2.5	38.98	7.787	6.817

TABLE 4.10 Heat rejection and % Rate of evaporation in case of cross flow

T1	T2	T3	TMW	TMA	TAV	Q	EVAP
30.0	24.0	33.0	30000.0	48720.1	27.38	.7360E+06	1.95
30.0	24.0	33.0	50000.0	48720.1	29.01	.8737E+06	1.65
30.0	24.0	33.0	70000.0	48720.1	29.92	.9443E+06	1.50
30.0	24.0	36.0	30000.0	48720.1	28.32	.1007E+07	2.23
30.0	24.0	36.0	50000.0	48720.1	30.48	.1209E+07	1.87
30.0	24.0	36.0	70000.0	48720.1	31.71	.1316E+07	1.67
30.0	22.0	33.0	30000.0	48720.1	25.34	.6730E+06	2.14
30.0	22.0	33.0	50000.0	48720.1	28.30	.1030E+07	1.78
30.0	22.0	33.0	70000.0	48720.1	29.38	.1111E+07	1.59
30.0	22.0	36.0	30000.0	48720.1	27.31	.1139E+07	2.42
30.0	22.0	36.0	50000.0	48720.1	29.78	.1361E+07	1.99
30.0	22.0	36.0	70000.0	48720.1	31.18	.1480E+07	1.76
35.0	29.0	38.0	30000.0	47927.1	31.68	.8352E+06	2.06
35.0	29.0	38.0	50000.0	47927.1	33.37	.1021E+07	1.77
35.0	29.0	38.0	70000.0	47927.1	34.37	.1121E+07	1.60
35.0	29.0	41.0	30000.0	47927.1	32.40	.1135E+07	2.41
35.0	29.0	41.0	50000.0	47927.1	34.62	.1407E+07	2.02
35.0	29.0	41.0	70000.0	47927.1	35.96	.1558E+07	1.80
35.0	27.0	38.0	30000.0	47927.1	30.51	.9891E+06	2.30
35.0	27.0	38.0	50000.0	47927.1	32.51	.1202E+07	1.92
35.0	27.0	38.0	70000.0	47927.1	33.73	.1318E+07	1.71
35.0	27.0	41.0	30000.0	47927.1	31.26	.1285E+07	2.62
35.0	27.0	41.0	50000.0	47927.1	33.81	.1584E+07	2.17
35.0	27.0	41.0	70000.0	47927.1	35.34	.1751E+07	1.91
40.0	34.0	43.0	30000.0	47157.5	35.99	.9339E+06	2.22
40.0	34.0	43.0	50000.0	47157.5	37.67	.1184E+07	1.90
40.0	34.0	43.0	70000.0	47157.5	38.74	.1325E+07	1.71
40.0	34.0	46.0	30000.0	47157.5	36.50	.1264E+07	2.59
40.0	34.0	46.0	50000.0	47157.5	38.68	.1626E+07	2.20
40.0	34.0	46.0	70000.0	47157.5	40.10	.1836E+07	1.95
40.0	32.0	43.0	30000.0	47157.5	34.67	.1108E+07	2.47
40.0	32.0	43.0	50000.0	47157.5	36.71	.1395E+07	2.07
40.0	32.0	43.0	70000.0	47157.5	37.99	.1557E+07	1.84
40.0	32.0	46.0	30000.0	47157.5	35.21	.1434E+07	2.83
40.0	32.0	46.0	50000.0	47157.5	37.75	.1832E+07	2.36
40.0	32.0	46.0	70000.0	47157.5	39.37	.2063E+07	2.08
45.0	39.0	48.0	30000.0	46411.5	40.34	.1028E+07	2.35
45.0	39.0	48.0	50000.0	46411.5	41.92	.1360E+07	2.04
45.0	39.0	48.0	70000.0	46411.5	43.04	.1556E+07	1.84
45.0	39.0	51.0	30000.0	46411.5	40.67	.1385E+07	2.76
45.0	39.0	51.0	50000.0	46411.5	42.69	.1858E+07	2.38
45.0	39.0	51.0	70000.0	46411.5	44.15	.2148E+07	2.13
45.0	37.0	48.0	30000.0	46411.5	38.87	.1225E+07	2.63
45.0	37.0	48.0	50000.0	46411.5	40.82	.1604E+07	2.23
45.0	37.0	48.0	70000.0	46411.5	42.16	.1829E+07	1.99
45.0	37.0	51.0	30000.0	46411.5	39.23	.1577E+07	3.03
45.0	37.0	51.0	50000.0	46411.5	41.62	.2096E+07	2.57
45.0	37.0	51.0	70000.0	46411.5	43.30	.2414E+07	2.28

TABLE 4.11 Various costs v/s flow rate

FMW	TMP	POWER	WATER	[illegible]	[illegible]	[illegible]
20000	48720	66317	110943	1414	44095	164795
30000	48720	92886	174126	2559	[illegible]	260971
50000	48720	77827	221230	1231	45104	[illegible]
60000	48720	90093	257781	1261	45434	359160
70000	48720	97210	304477	1222	45833	402910
80000	48720	105930	317909	1479	46314	455280
20000	29232	25731	116290	2870	29095	144693
20000	38976	42545	117048	1905	35035	161138
20000	48720	66317	110943	1414	41035	164795
20000	58464	96041	117109	1173	53095	216389
20000	68208	142355	177109	1031	61095	260520
30000	48720	92886	174426	2553	44410	269371
30000	58464	135759	176245	2091	53410	314096
30000	68208	191416	174739	1727	61411	367083

APPENDIX

```
C***********************************************************************
C                                                                      *
C                        O P T I M U M                                 *
C                                                                      *
C          D E S I G N   O F   C O O L I N G   T O W E R               *
C                                                                      *
C***********************************************************************
C  COOLING TOWER DESIGN
C  CROSS FLOW TYPE
C  WITH VARIABLE MASS OF WATER (i.e., with consideration of evaporation
C       of water At Every Grid Point)
C       EXTENSION of paper by Baker and Shryock
C- A COMPREHENSIVE APPROACH TO THE ANALYSIS OF COOLING TOWER PERFORMANCE

      DIMENSION S1(30,30), S2(30,30), S22(30,30), S3(30,30), DW(30,30)
      DIMENSION DAW(30,30), WSE(30,30), WSE(30,30), ALEE(30,30)
      DIMENSION VOLAR(30,30), VOLAB(30,30), DET(30,30), ENDIFF(30,30)
      DIMENSION ENWAT(30,30), ENDL(30,30), FRENDT(30,30), WSS(30,30)
      DIMENSION ENMEAN(30,30), ATU(30,30), SUMATU(30,30), TOCH(30,30)
      DIMENSION TOWERC(30,30), RANGE(30,30), WATEV(30)

      REAL NTU, LENGTH, LATOTA, LHIGH, MASWAT, MASAIR, NOUARE
      REAL MOTLOW, MOTLOW, MODPCK, LWYEAR
      INTEGER ARRANG

C     ===================================================================
C     Functional sub-programs
C     ===================================================================
      P(X)=1.00456E-2.07C7E-5*X+9.1+15E-7*X**2
      P(X)=223.0584+0.81/EXP((7.21379+((1.152E-5-4.787E-9*(273.16+X))*
     1((X-210)**2)))*(647.31/(273.15+X)-1))
      TR(X)=(1.8*X+32)+459.67
      CPA(X)=(0.219+0.342E-04*TR(X)-0.297E-08*TR(X)**2)*4.187
      CPW(X)=4.2097187-1.4125E-03*X+1.375E-05*X**2
      HFG(X)=(597.34-0.555*X-0.2369*10**(5.1463-1540/(X+273.16)))*4.18
     17
      HF(X)=(0.99615*X+(1.9239E-6)*X**2-0.13468*10**(-0.036*X)+0.1346
     18)+4.187
      HG(X)=HFG(X)+HF(Y)
      DEN(X)=1.291-(4.525E-3*X)+1.125E-5*X**2
      TCK(X)=0.0207+(6.5E-5*X)-(2.5E-7*X**2)
      VISA(X)=1.325E-5+8.525E-8*X+1.525E-10*X**2
      YE(X)=0.333*ALOG10(X)**2+0.177345*ALOG10(X)+2.6949E-3
      PCOST(X)=1.2930/(0.9786+EXP(-0.09538*X))
C     ===================================================================

      OPEN (UNIT=20, FILE='DAT.CDR')
      OPEN (UNIT=01, FILE='COST.ALL')
      OPEN (UNIT=21, FILE='ECONM.FAC')
      OPEN (UNIT=22)
      OPEN (UNIT=40)
      SPVOLA=0.85
      READ (20,*), M, N, LENGTH, LWIDTH, LHIGH, RP, DENWAT, C1, C2
      READ (20,*), GRAV, AVDFAR, GASCON
      READ (20,*), ARRANG
      READ (20,*), SIDE1, SIDE2
      READ (20,*), FANEFF, UF, PUMEFF
      READ (20,*), YEAR
      READ (20,*), WATCUS, WODCFT
      READ (20,*), GMAS, ONLVG
      READ (20,*), VELWAT, PIPEFT
      READ (20,*), DRIFT, BLDOWN
      READ (20,*), LIFE, RATINT
C     ARRANG-If ARRANG IS 1---TRIANGULAR SLATS
C                         2---RECTANGULAR SLATS
      IF (ARRANG .EQ. 1) GO TO 67
      IF (ARRANG .EQ. 2) GO TO 68
67    A1=10; A2=0.028
      PER1=SIDE1+SIDE2+SQRT(SIDE1**2+SIDE2**2)
      AREAF=(SIDE1*SIDE2)/2
      GO TO 60
68    A1=12.9; A2=0.072
      PER1=(SIDE1+SIDE2)*2
      AREAF=SIDE1*SIDE2

60    FYEAR=YEAR/4
      IYEAR=FYEAR
      IF(ABS(FYEAR-IYEAR) .EQ. 0.0) GO TO 22
      HRYEAR=365*24
      GO TO 23
22    HRYEAR=366*24
23    CFMTFT=0.3048
      CFKGLB=0.45359
      CAOUR=WOODCFT*1.4/CFMTFT**3
```

```
      IF (T3 .LE. 40) GO TO 30
      T1=T3
      T2=T1-15
      T3=T1+5
      DESTAV=T3-15
      IF (T3 .GT. 43) GO TO 30
      PRINT 51, T1, T2, T3
C
C     ==================================================================
C     T1=TEMPERATURE OF AIR (DRY BULB TEMPRATURE -TDB  IN DEGREE C)
C     T2=TEMPERATURE OF AIR (WET BULB TEMPRATURE - TWB IN DEGREE C)
C     T3=TEMPERATURE OF HOT WATER (IN DEGREE C)
C     DESTAV=Desire Temprature Of Outlet Water (In Degree C)
C     TAV-Average Temprature of water leaving the tower in C
C     V=velocity of air in m/sec
C     VEIN = Velocity of air in m/min
C     ALPHA=REYNOLDS NUMBER
C     PR=PRANTAL NUMBER
C     TC1 = thermal conductivity of air in kcal/m-hr-C
C     VISK = Kinematic viscosity in m**2/sec
C     TMA=mass of air in Kg/hr
C     TMW=mass of water in Kg/hr
C     CPKGLB=Conversion Factor from Pound to Kg and vice versa
C     CFMTFT=Conversion factor from Meter to Feet and vice versa
C     DENWAT=Density of water in Kg/m**3(i.e., 1000)
C     DEN= Density of Air in Kg/m**3
C     C(1)=Coefficient which is a function of temprature & Pressure
C     CPA(=1.0250)=Specific heat of dry air in KJ/ C-Kg
C     HC=Heat transfer Coefficient in Kcal/hr-m**2-C
C     HD=Mass transfer Coefficient in Kg of dry air/hr-m**2
C     P1 & P2 (Pressure)=In terms of N/m**2
C     N=Number Of Grid Divisions For Calculation Purpose
C     NP=Actual Number Of Grid Points Available For Calculation
C     FLENTH=Length of Fill Material in m
C     EQDIA=Equivalent Diameter of Fill Material in m
C     AR=Area Of Cross Section Of Fill Material in m**2
C     G1=Temprature Of Water At Every Grid Point
C     G2=Humidity Of Air At Every Grid Point
C     G3=Enthalpy of Air At Every Grid Point
C     Q1=Heat Absorbed By Air From Hot Water In The Process of Cooling
C     Q2=Heat Given Out From Hot Water To Air
C     NX=Number of Fills Along The Length of Tower
C     NY=Number of Fills Along The Height of Tower
C     NOUNAR=Number of Fills per Unit Area
C     NOFLWD=Number of Fills along the Width of the Tower
C     NOFLHT=Number of Fills along the Height of the Tower
C     DISTHT=Distance Between Each Fill(along height)
C     DISWDT=Distance Between Each Fill(along width)
C     VSUP=Superficial velocity
C     SPVOLA=Specific volume of air
C     NTU=Number of Transfer Units
C     TCH=Tower Characteristic
C     ==================================================================
C
      FLENTH=FLENGH*CFMTFT
      HEIGHT=HEIGHT*CFMTFT
      WIDTH=WIDTH*CFMTFT
      DO 31 K2=1,5,2
      DO 26 IVEL=3,5
      V=IVEL*0.5
      IF (V .GE. 2.5) GO TO 26
      VEIN=V*60
      DEN=1.32E-4*(T1+T3)/2+0.84448
      C=0.75*ALPHA+0.25
      PH=0.090428-0.00726*ALPHA
      ALT=C+PH*XP(VEIN)
      VOLSEC=HEIGHT*FLENTH*V
      VOL=VOLSEC*3600
      TMA=VOL*DEN(T1)
      TMW=FLOAT((K2+2)*10000)
      IF (TMW .GT. 30000) GO TO 31
      IF (TMW .NE. 50000) GO TO 31
      IF (TMW .EQ. 50000.0) DESTAV=T3-7
      IF (TMW .EQ. 70000.0) DESTAV=T3-6
      IVER=1
      RAA=TMA/M
      TYPE *, T1, T2, T3, DESTAV, V, TMW, TMA
      TYPE 25
C
C     ==================================================================
C      Calculation of Reynold's Number & Friction factor
C     ==================================================================
C
      EQDIA=PEPI/3.1415926
      DI=EP(1,2)
```

```
      HA=CPA(T1)*T1+WA*(2501.+1.884*T1)
      HV=P(13)*P(13)
      ENV=0.622*A /(P-A)
      HB=CPA(T2)*T3+WSU*(2501.1+1.884*T3)
      PRINT 101, HA, HB
      GA=(TMA/18)/(DEN(T1)*(4*2.54E-02-EODTA)*LENTH)
      RE=GA*EQDIA/(VISK(T1)*3600)
      FRTFAC=(0.25+0.118/((4*2.54E-02/EQDIA-1)**1.08))*((GA*EQDIA/(VIS
     1K(T1)*DEN(T1)*3600))**-0.16)
      CPMA=CPA(T1)+WA*1.884
      PR=DEN(T1)*VISK(T1)*CPMA*3600/(TCK(T1)*4.187)
      HC=((0.171*TCK(T1)*PR**0.35*(V/VISK(T1))**0.78)/(EODTA**0.22
     1))*1.0*4.187
      HD=HC/(ALE*CPMA)
      GO TO 74
72    NOFILL=NOTUB-2
      GO TO 73
74    DO 700 NOTUB=250,2510,50
73    FLAREA=NOTUB*PERI*FLENTH
      VOLU=HEIGHT*WIDTH*LENTH
      AV=FLAREA/VOLU
      TEVA=FLAREA/(ASTAF*NOFILL)
      DVID=VOLU/(A*H)
      G=HD*AV*DVID/TMA
      HDAV=HD*AV
      ED=HA* /(TM *CPW(13))
      ATUBE=NOTUB/(ATOTA*HEIGHT)
      NORIZ=SQRT(NUBAPE)*HEIGHT
      NOTIN=SQRT(NUBAPE)*WIDTH
      DISBE=HEIGHT/NOFILL
      DISPT=ATOTA/DISPEH
      IF ((DISBEP-2*SIDE1) .LE. 0.00) GO TO 28
28    IF ((DISPEH-2*SIDE2) .LT. 0.00) GO TO 24
      GO TO 27
24    TYPE 20
      TYPE 140
C     PAUSE
      GO TO 20
27    NODECK=HEIGHT/DISBEH
      IET=NODECK
      IF(ABS(NODECK-IET) .GE. 0.5) GO TO 12
      GO TO 13
12    NODECK=IET+1
      GO TO 14
13    NODECK=IET
14    VSUP=VOLU/(LENTH*WIDTH)
      HCT=A1*(1-A2*DISPEH/EQDIA)*(VSUP**0.75/EODTA*0.28)

C     ==================================================================
C      CALCULATION OF PRESSURE DROP IN TERMS OF INCHES OF WATER
C      CALCULATION OF COST OF POWER
C     ==================================================================
C      AIRDEN-Density of Air at T1 in Lb/Ft**3
C      WATDEN-Density of water in Lb/Ft**3
C      MASAIR-Mass of Air in Lb/hr per unit plan area
C      MASWAT-Mass of Water in Lb/hr per unit plan area
C      PRDROP-Pressure Drop in Terms of INCHES of Water per Fill
C      PRPERF-Pressure Drop per Fill in MILLIMETER of Water
C      DELPR-Total Pressure Drop in Terms of MILLIMETER of Water
C      C1 & C2-Constants depending on Deck Arrangement(depending
C             on vertical spacing
C      GRAV-Acceleration Due to Gravity in Ft/sec**2
C      UNIVG-Universal Gravitational Constant
C      GMKS-Acceleration due to Gravity in M/sec**2
C      AVDEAR-Average Dry Air Density in Lbs/Ft**3
C      LENGTH,LWIDTH,LHIGH-Dimensions of Tower in FPS Units
C      NODECK-Number of Decks used in the Tower(no. of rows)
C     ==================================================================

      AIRDEN=DEN(T1)*CFMTFT**3/CFKGLB
      WATDEN=DENWAT*CFMTFT**3/CFKGLB
      MASAIR=TMA/(CFKGLB*LENGTH*LWIDTH)
      MASWAT=TMW/(CFKGLB*LENGTH*LWIDTH)
      ZF=DISBEH*2/(CFMTFT*RP)
      AIRGE=MASAIR**2+((4*MASAIR*3600*AIRDEN)*SQRT(2*GRAV*ZF))/3+GRAV*
     1ZF*(3600*AIRDEN)**2
      PRDROP=(AVDEAR/AIRDEN)*(C1*MASAIR**2+C2*SQRT(ZF)*MASWAT*AIRGE)
      PRPERF=PRDROP*25.4
      DELPR=NODECK*PRPERF
      FANPOW=DELPR*GMKS*DENWAT*VOLSEC/(1000*FANEFF*UNIVG)
      PUHEAD=HEIGHT+1.0
      PIPDIA=SQRT(TMA/(DENWAT*VELWAT*3.1415926))
      FRHEAD=PIPFRT*PUHEAD*VELWAT**2/(2*PIPDIA*GMKS)
      TOHEAD=PUHEAD+FRHEAD
      PUMPOW=TOHEAD*TMW*GMKS/(3600*PUMEFF*UNIVG)
```
[redacted]

```
C     ... of water, humidity of air, enthalpy
C     of air at every Grid Point
C     ====================================================================

      H=HHIN
      DO 111 I=1,M
      S2(1,1)=WA
      S3(1,1)=HA
      DO 111 J=1,N
      S1(I,J)=TS
      TJ=S1(I,J)
      W=S2(I,J)
      H=S3(I,J)
      IF (I .EQ. 1) GO TO 70
      GO TO 80
70    TJ=T3
      W=WA
80    IF (J .EQ. 1) GO TO 90
      AB=P(IJ)*P(IJ)
      WS=0.622*AB/(PA-AB)
      HS=CPA(IJ)*TJ+WS*(2501.4+1.884*TJ)
      GO TO 100
90    W=WA
      H=HA
      IF (I .GT. 1 .AND. J .EQ. 1) GO TO 222
      GO TO 100
222   AB=P(IJ)*P(IJ)
      WS=0.622*AB/(PA-AB)
      HS=CPA(IJ)*TJ+WS*(2501.4+1.884*TJ)
100   DW(I,J)=G*(WS-W)

C     ====================================================================
C     Calculation of Lewis Number at every grid point
C     ====================================================================

      TEMP=(HS-WS*2501.4)/(1.004+1.884*WS)
      ALPHA=1.32E-4*((TJ+TEMP)/2+0.84418
      C=0.75*ALPHA+0.25
      ZA=0.0042*PA-0.00726*ALPHA
      ALE=C+ZA*XF(VAIR)
      ALSE(I,J)=ALE
      ALESUM=ALE+ALESUM
      GH=ALE*(HS-H)/(WS-W)+HG(TJ)-ALE*2501.4
      DH=GH*DW(I,J)
      IF (I .EQ. 1) GO TO 10
      GO TO 343
10    DMW(1,J)=XMW/N
343   DT=(DH-DMW(I,J)*HF(TJ))/(DMW(I,J)*CPW(TJ)/DMA)
      DTT(I,J)=DT
      ENDIFF(I,J)=DH
      HSAT(I,J)=HS
      ENDI(I,J)=HS-H
      RENDI(I,J)=1/ENDI(I,J)
      WSE(I,J)=WS
      TJ=TJ-DT
      W=W+DW(I,J)
      H=H+DH
      HSE(I,J)=HS
      WSE(I,J)=WS
      DMW(I+1,J)=DMW(I,J)-DMA*DW(I,J)
      S1(I+1,J)=TJ
      S2(I,J+1)=W
      S3(I,J+1)=H
111   CONTINUE
      MD=M+1
      ND=N+1

C     ====================================================================
C     Calculation of volume >>> based on water evaporation rate
C     ====================================================================

      NDD=N-1
      SVOLWB=0
      DO 151 I=1,M
      DO 151 J=1,NDD
      VOLWB(I,J)=((DW(I,J)+DW(I,J+1))*0.5)*0.5*(1/(WSE(I,J)-S2(I,J))+
     1 1/(WSE(I,J+1)-S2(I,J+1)))
      SVOLWB=SVOLWB+VOLWB(I,J)
151   CONTINUE

C     ====================================================================
C     Calculation of volume >>> based on enthalpy of air
C     ====================================================================

      SVOLHB=0
      DO 152 J=1,N
```

```
      ... [illegible] (I,J)=HE(S1(I+1,J))/(DELT,J-S1,J)*[illegible]
      SVOLHE=SVOLHE+VOLHE(I,J)
 152  CONTINUE
      TVOLUM=SVOLUM*D.A/(ND*AV)
      TVOLHE=SVOLHE+TAH/(ND*AV*W)
C     TYPE *, TVOLUM, TVOLHE

C     ====================================================================
C      Calculation of Average
C        Lewis number, outlet temprature of Water, humidity & Enthalpy
C     ====================================================================

      TI=S1(MD,1)
      DMASUM=DMW(MD,1)
      HEFE=DMW(MD,1)*HF(S1(MD,1))
      DO 15 J=2,N
      DMASUM=DMW(MD,J)+DMASUM
      HEFE=HEFE+DMW(MD,J)*HF(S1(MD,J))
 15   TI=TI+S1(MD,J)
      HEFAVE=AHESUM/(M*N)
      EVAP=TMW-DMASUM
      TAV=TI/N
      IF (DESTAV .GT. TAV) GO TO 500

C     ====================================================================
C      Calculation of Makeup water used in Tower and Cost of water
C     ====================================================================
C      WATEV=water evaporated at each Grid
C      TMKWEV=Total Mass of Water Evaporated
C      TOTWYE=Total Water Used per Year
C      WATCOS=Cost of Water per Cubic Meter
C      CWATER=Total Cost of Water
C     ====================================================================

      TMKWEV=0.0
      DO 21 I=1,M
      WATEV(I)=DMA*(S2(I,J+1)-S2(I,1))
      TMKWEV=TMKWEV+WATEV(I)
 21   CONTINUE
      OTLOSS=TMW*(DRIFT+BLDOWN)/100
      TOTWYE=(TMKWEV+OTLOSS)/DENWAT
      CWATER=TOTWYE*WATCOS*HRYEAR*DF
      TYPE *, ITER, NOFILL, TAV, NODECK, DELPR, CPOWER, TOTWYE, CWATER
      NNDECK=NODECK
C     TYPE 333, ITER, NOFILL, NNDECK, T1, T2, T3, DESTAV, V, TMW, TAV
      GO TO 322
      PRINT 131
      DO 322 I=1,MD
      PRINT 323, (S1(I,J), J=1,N)
 322  CONTINUE
      ITER=ITER+1
 700  CONTINUE

 500  IF (ABS(TAV-DESTAV) .LT. 0.06) GO TO 71
      TYPE *, ITER, NOFILL, TAV, NODECK, DELPR, CPOWER, TOTWYE, CWATER
C     TYPE 333, ITER, NOFILL, NNDECK, T1, T2, T3, DESTAV, V, TMW, TAV
      GO TO 324
      PRINT 131
      DO 324 I=1,MD
      PRINT 323, (S1(I,J), J=1,N)
 324  CONTINUE
      ITER=ITER+1
      GO TO 72
 71   TYPE 140
      FILVOL=AREAF*FLENTH
      TOPOD=FILVOL*NOFILL
      COFILL=TOPOD+CAPOD
      WRITE (01,*), FANPOW, PUMPOW, CPOWER, CWATER, COFILL
      TOTCO=CPOWER+CWATER+COFILL
      WRITE (40,*), TMW, CPOWER,CWATER,COFILL,TOTCO
C     PAUSE
C     GO TO 201
      LLIFE=1+LIFE
      TOTPOC=0.0
      TOTWAC=0.0
      TOTWOC=0.0
      WRITE (21,*), T1, T2, T3, DESTAV, V, TMW, TMA
      WRITE (21,*), ITER, NOFILL, TAV, NODECK, DELPR, CPOWER, TOTWYE,
     1CWATER
      WRITE (21,25)
      DO 201 LITO=1,LLIFE
      LITOW=LITO-1
      COSTP=CPOWER/(1+RATINT)**LITOW
      COSTWA=CWATER/(1+RATINT)**LITOW
      COSTWO=COFILL/(1+RATINT)**LITOW
      TOTPOC=TOTPOC+COSTP
```

```
      [illegible]
      WRITE (21,*), IRTU, TOTBUC, TOLVAT, TOTWUC, IOIABC
      IF (UNIT .NE. INIT) GO TO 201
      WRITE (21,130)
201   CONTINUE

      WRITE (22,977), VOLW, M, N
      WRITE (22,978), T1, T2, T3, T4, TMA, HA, WA
      DO 385 I=1,ND
      DO 385 J=1,ND
385   S2(I,J)=S2(I,J)*1000
      DO 701 J=1,N
701   PRINT 307, J, (S1(I,J), I=1,M)
      GO TO 101
      PRINT 131
      DO 101 I=1,ND
      PRINT 132, (S1(I,J), J=1,N)
101   CONTINUE
      PRINT 133
      DO 102 I=1,M
      PRINT 134, (S2(I,J), J=1,ND)
102   CONTINUE
      PRINT 135
      DO 103 I=1,M
      PRINT 136, (S3(I,J), J=1,ND)
103   CONTINUE
101   CONTINUE
      PRINT 137
      DO 104 I=1,M
      PRINT 138, (DW(I,J), J=1,N)
104   CONTINUE
      PRINT 139
      DO 105 I=1,ND
      PRINT 141, (DMW(I,J), J=1,N)
105   CONTINUE
      PRINT 140
      HH=S3(1,ND)
      WW=S2(1,ND)
      DO 16 I=2,M
      HH=HH+S3(I,ND)
16    WW=WW+S2(I,ND)
      HAV=HH/M
      WAV=WW/M
      RATE=EVAP*100/TMW
C     TYPE *,RATE
      PRINT 5, TVOLWR, TVOLHR, EVAP, RATE
      PEREVE=EVAP/TMW*100
      PRINT 91
      PRINT 92, M, N, V, G, R, ALEAVE, TMA, WAV, HAV, TAV,TMW
      HH2=0.
      DO 2 I=1,3
2     HH2=HH2+S3(I,ND)
      HHH2=HH2-3*HA
      HH3=0.
      DO 3 I=10,15
3     HH3=HH3+S3(I,ND)
      HHH3=HH3-6*HA
      HH4=0
      DO 7 I=4,9
7     HH4=HH4+S3(I,ND)
      HHH4=HH4-6*HA
      THH=HH-M*HA
      TOP=100*HHH2/THH
      BOT=100*HHH3/THH
      MID=100*HHH4/THH
      SUMHH=TOP+BOT+MID
C     TYPE *,SUMHH
      Q1=D4A*THH
      Q2=TMW*HF(T3)-HEFF
      PRINT 17, Q1, Q2
      PRINT 4, TOP, BOT, HDAV
      SUMNTU(1,1)=0.0
      TOWERC(1,1)=0.0
      RANGE(1,1)=DTT(1,1)
      DO 77 I=1,M
      DO 77 J=1,N
      ENMEAN(I,J)=(FRENDT(I,J)+FRENDT(I+1,J))/2
      NTU(I,J)=DTT(I,J)*ENMEAN(I,J)
      SUMNTU(I,J)=SUMNTU(I,J-1)+NTU(I,J)
      TOCH(I,J)=(ENDTFF(I,J)+ENDTFF(I+1,J))*ENMEAN(I,J)/2
      TOWERC(I,J)=TOWERC(I,J-1)+TOCH(I,J)
77    CONTINUE
      DO 78 J=1,N
      DO 78 I=1,M
      RANGE(I,J)=RANGE(I,J-1)+DTT(I,J)
78    CONTINUE
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      WRITE (22,883), (S3(I,J), J=1,N)
970   CONTINUE
      GO TO 33
      DO 33 I=1,MD
      TYPE 40, (S1(I,J), J=1,ND)
      IF (I .EQ. MD) GO TO 33
      TYPE 41, (S2(I,J), J=1,ND)
      TYPE 42, (S3(I,J), J=1,ND)
      TYPE 43, (ENWAT(I,J), J=1,N)
      TYPE 44, (ENDI(I,J), J=1,N)
      TYPE 45, (FRENDI(I,J), J=1,N)
      TYPE 46, (ENMEAN(I,J), J=1,N)
      TYPE 47, (NTU(I,J), J=1,N)
      TYPE 48, (SUMNTU(I,J), J=1,N)
      TYPE 49, (TUCH(I,J), J=1,N)
      TYPE 50, (TOWERC(I,J), J=1,N)
      TYPE 63, (RANGE(I,J), J=1,N)
      TYPE 140
33    CONTINUE
      GO TO 543
      WRITE (40,834), T1, T2, T3, TMW, V, TAV, VOLH, TVOLWB
      WRITE (40,25)
543   CONTINUE
25    CONTINUE
31    CONTINUE
30    CONTINUE
1     FORMAT (//,7X,'ENTHALPY------->',7X,'TOP 20%=',E12.4,8X,'BOTTOM 4
     10%=',F12.4,4X,'HD*AV=',F10.4//////)
5     FORMAT (5X, 'VOLUME OF TOWER BASED ON HUMIDITY  =', E16.4, 5X,
     1'VOLUME OF TOWER BASED ON ENTHALPY  =', E16.4, /, 5X, 'MASS OF
     2 WATER EVAPORATED =' F11.4, 5X, 'RATE OF EVAPORATION=' E11.4)
      WRITE (22,880)
      WRITE (22,891)
      WRITE (22,884), TAV, HAV, WAV, EVAP, Q1, NOFILL, TVOLWB
17    FORMAT (/,5X, 'Q1=',E15.8,5X, 'Q2=',E15.8)
25    FORMAT (/)
29    FORMAT (5X, 'DISTANCE BETWEEN FILL > TWICE THE SIZE OF THE FILL')
40    FORMAT (8X, 'T', 4X, 10F10.4)
41    FORMAT (8X, 'W', 4X, 10F10.4)
42    FORMAT (8X, 'H', 4X, 10F10.4)
43    FORMAT (4X, 'ENWAT', 4X, 10F10.4)
44    FORMAT (5X, 'ENDT', 4X, 10F10.4)
45    FORMAT (3X, 'FRENDT', 4X, 10F10.4)
46    FORMAT (3X, 'ENMEAN', 4X, 10F10.4)
47    FORMAT (6X, 'NTU', 4X, 10F10.4)
48    FORMAT (3X, 'SUMNTU', 4X, 10F10.4)
49    FORMAT (5X, 'TOCH', 4X, 10F10.4)
50    FORMAT (2X, 'SUMTOCH', 4X, 10F10.4)
51    FORMAT (///,7X,'T1=',E8.3,4X,'T2=',E8.3,4X,'T3=',E8.3)
63    FORMAT (4X, 'RANGE', 4X, 10F10.4)
91    FORMAT (4X,'M',5X,'N',6X,'V',9X,'G',11X,'R',8X,'ALEAVE',9
     1X,'TMA',11X,'WAV',12X,'HAV',12X,'TAV',12X,'TMW')
92    FORMAT (2(4X,I2),4X,F3.1,2(4X,F8.6),4X,F6.4,4X,F12.3,4(4X,
     1E11.4))
131   FORMAT(//, 4X, 'Details Of Water Temperature At Every Grid Point
     1', /)
132   FORMAT (4X, 'T', 4X, 10E11.4)
133   FORMAT (//, 4X, 'Details Of Humidity in Air At Every Grid Point'
     1,/)
134   FORMAT (4X, 'W', 4X, 10E11.4)
135   FORMAT (//, 4X, 'Details Of Enthalpy Of Air At Every Grid Point'
     1,/)
136   FORMAT (4X,'H',4X,10E11.4)
137   FORMAT (//, 4X, 'Details Of Water Evaporation At Every Grid Poin
     1t', /)
138   FORMAT (3X, 'DW', 4X, 10E11.4)
139   FORMAT (//, 4X, 'Details Of Water Available For Cooling At Every
     1Grid Point', /)
141   FORMAT (2X, 'DMW', 4X, 8E15.8)
140   FORMAT (//)
171   FORMAT (1X, 'VOLW', 4X, 10E11.4)
172   FORMAT (1X, 'VOLH', 4X, 10E11.4)
173   FORMAT (2X, 'WSE', 4X, 10E11.4)
181   FORMAT (/,5X, 'HA=', E11.4, 5X, 'WA =', E11.4,/)
323   FORMAT (2X, 17F7.3)
333   FORMAT (3X, I2, 3X, I4, 3X, I3, 3X, F4.1, 3X, F4.1, 3X, F4.1, 3X
     1, F4.1, 3X, F3.1, 3X, F7.1, 3X, F6.3)
834   FORMAT (8X, F4.1, 2X, F4.1, 2X, F4.1, 2X, F7.1, 2X, F3.1, 2X,
     1F5.2, 2X, F6.3, 2X, F6.3, 2X, F6.3)
387   FORMAT (3X, I2, 15(F7.3))
877   FORMAT (//,10X,'VOLUME OF TOWER USED =', F7.3,' M**3',/,10X,'NUM
     1BER OF GRIDS USED =',I2,' X ',I2,/)
878    FORMAT (/,10X,'INLET CONDITIONS :',/,15X,'Dry bulb temperature
     1 of Air',12X,'=',F7.2,' C',/,15X,'Wet bulb temperature of air',
     213X,'=',F7.2,' C',/,15X,'Water temperature on to the Tower',/X
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      [illegible] kg/kg of dry air',//)
 829  FORMAT (10X,8('!',14('-')),'!')
 830  FORMAT (10X,'!',11('-'),7('!',8('-'))'!')
 831  FORMAT (10X,'!',1X,'T=',15(1X,F5.3,1X,'!'))
 832  FORMAT (10X,'!',1X,'W=',15(1X,F5.3,1X,'!'))
 833  FORMAT (10X,'!',1X,'H=',15(1X,F5.3,1X,'!'))
 834  FORMAT (//,10X,'OUTPUT CONDITIONS :',/,15X,'Average temperature o
     1 leaving water',3X,'=',F7.2,' C',/,15X,'Average enthalpy of lea
     2ving air',8X,'=',F7.2,' kJ',/,15X,'Humidity of leaving air',16X
     3,'=',F7.6,' kg/kg of dry air',//,10X,'RESULTS :',/,15X,'Mass of
     4 water evaporated',15X,'=',F7.1,' kg/hr',/,15X,'Heat released',
     526X,'=',F10.1,' kJ/hr',/,15X,'Number of fill required',16X,'=',
     6I3,/,15X,'Volume of tower based on',/,20X,'evaporation rate',
     712X,'=',F7.1,' M**3')
 835  FORMAT (/,12X, 'Read humidity at each grid = w*1000',/)
      STOP
      CLOSE (UNIT=20)
      CLOSE (UNIT=21)
      CLOSE (UNIT=21)
      END
```